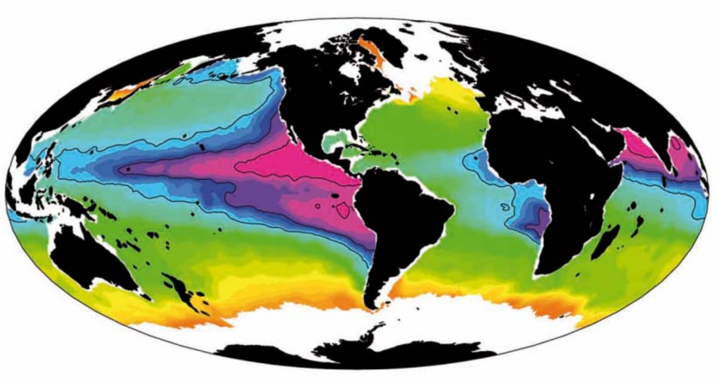


Oxygen Supply to the Tropical North East Atlantic Oxygen Minimum Zone

Tim Fischer, Johannes Hahn

Peter Brandt, Richard Greatbatch, Arne Körtzinger, Toste Tanhua, Martin Visbeck

Donata Banyte, Marcus Dengler, Gerd Krahmann

SFB 754

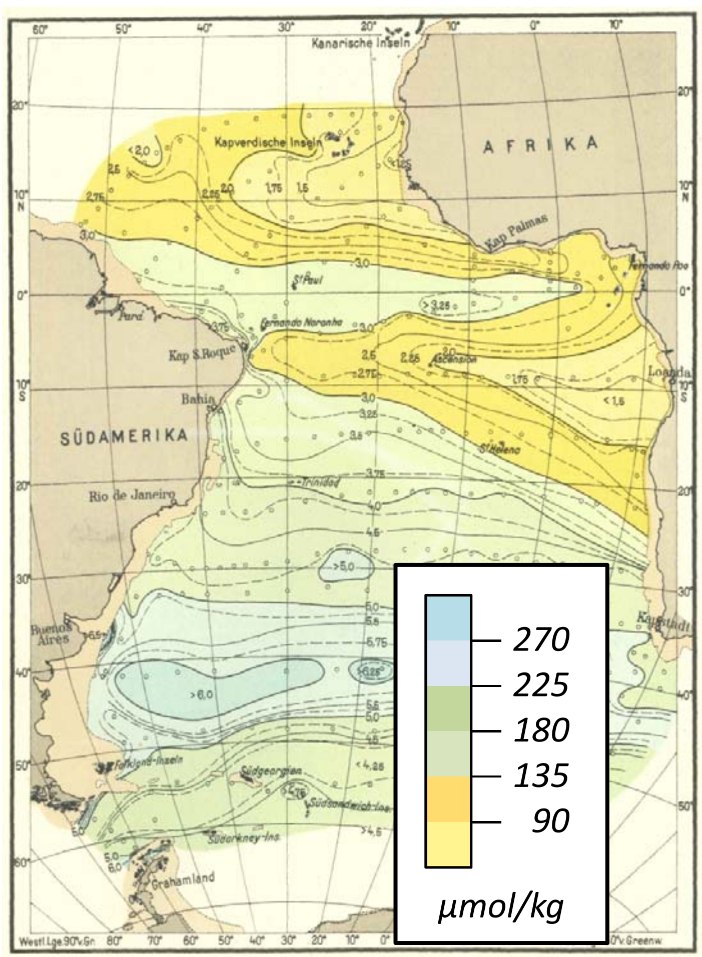
GEOMAR

Helmholtz Centre for Ocean Research Kiel

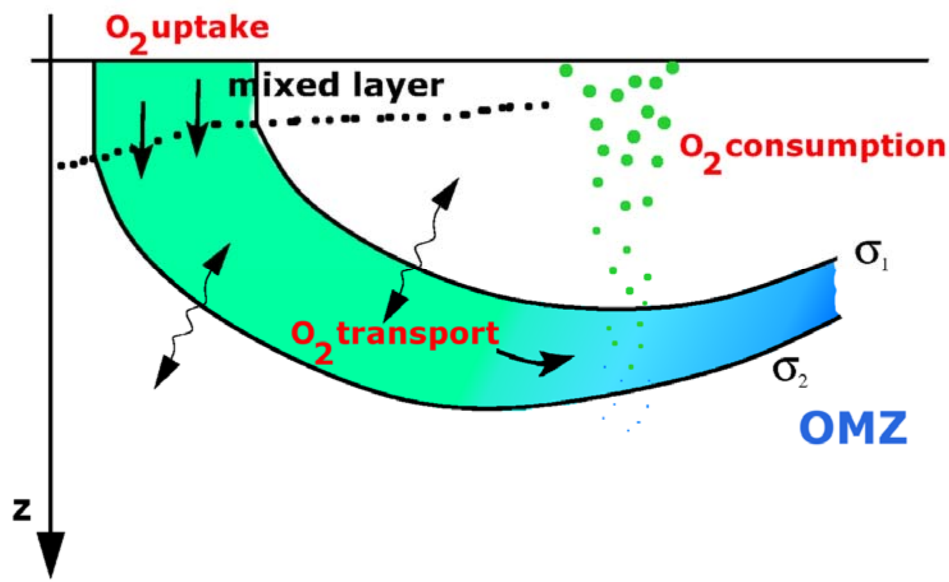
18.11.2013

Low oxygen in the open ocean

O_2 distribution at 600m obtained from the *Meteor* expedition 1925 – 1927 (*Wattenberg, 1939)*

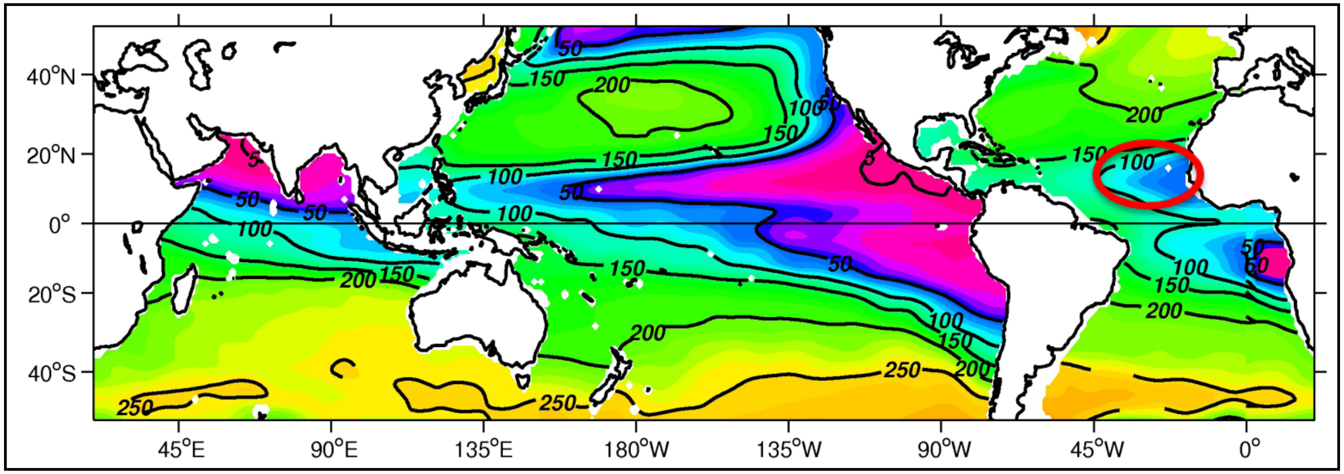


Pocesses influencing the oxygen concentration in the open ocean



Karstensen et al. 2008

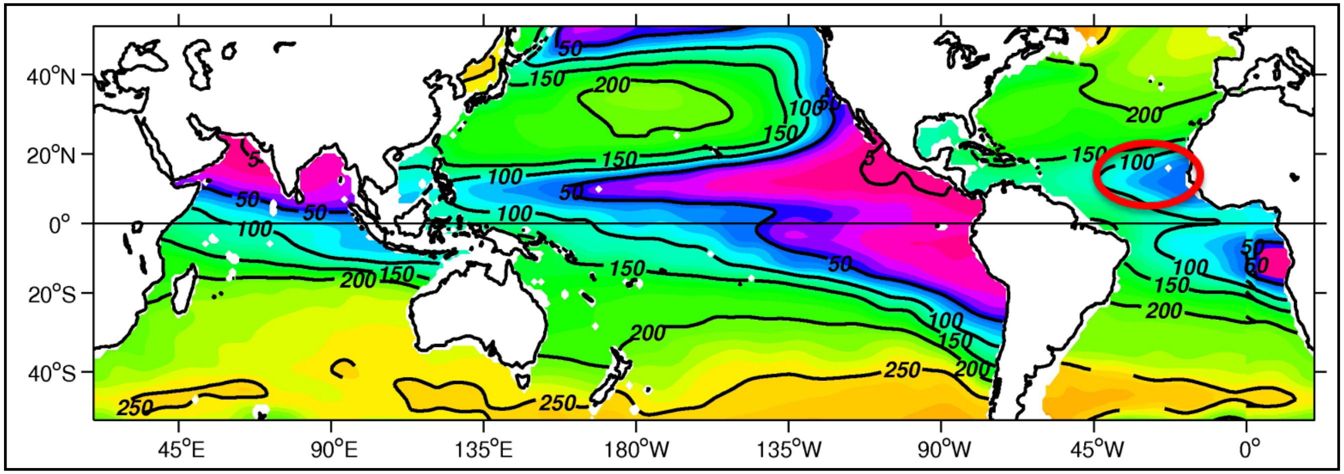
Low oxygen in the open ocean



O_2 distribution at 400m, in µmol/kg

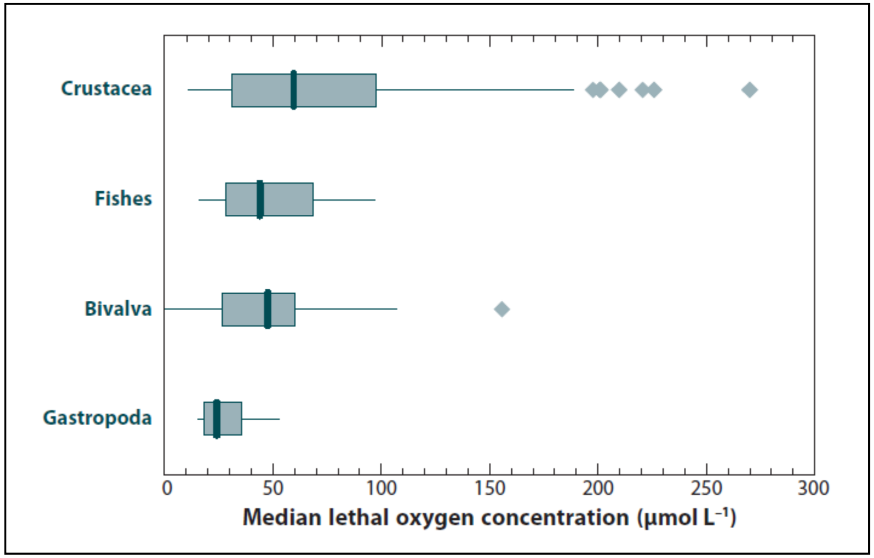
(Karstensen et al. 2008)

Low oxygen in the open ocean



O_2 distribution at 400m, in µmol/kg

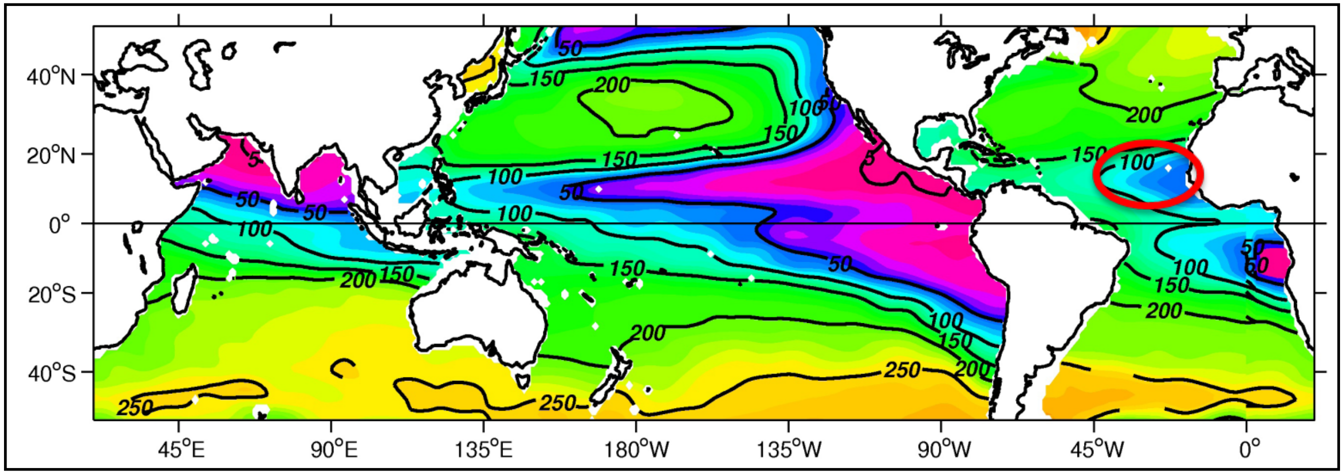
(Karstensen et al. 2008)



Sensitivity of marine organisms to low oxygen

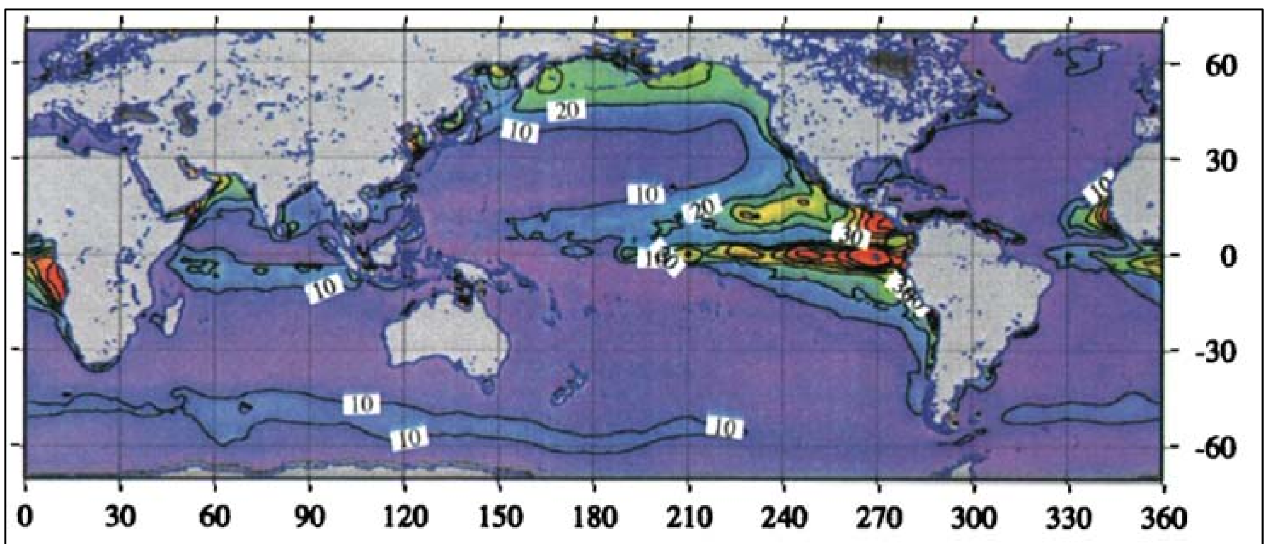
(Keeling et al. 2010, After Vaquer-Sunyer and Duarte 2008)

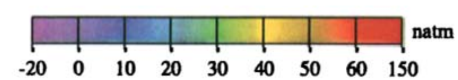
Low oxygen in the open ocean



O_2 distribution at 400m, in µmol/kg

(Karstensen et al. 2008)

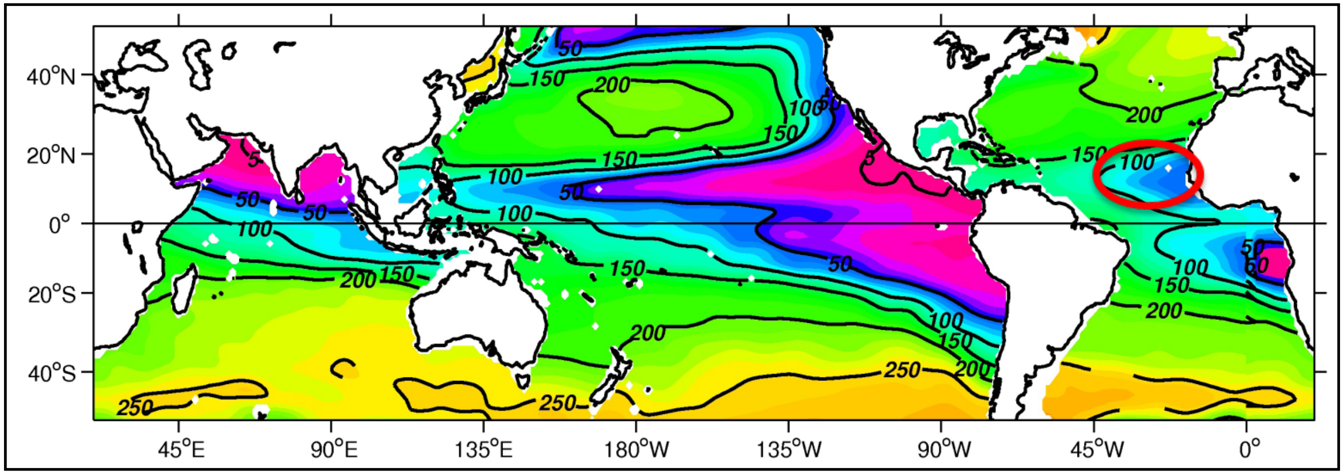




Outgassing of supersaturated N_2O

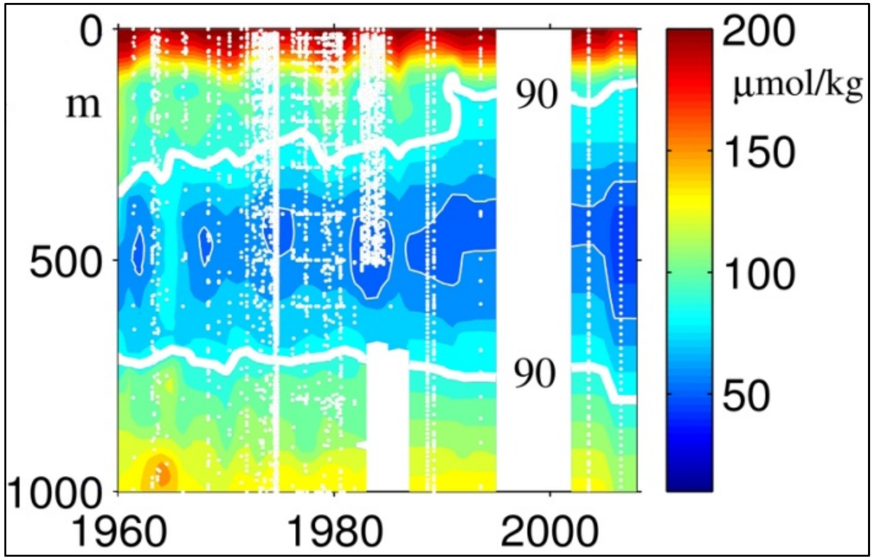
(Suntharalingam 2000)

Low oxygen in the open ocean



O_2 distribution at 400m, in µmol/kg

(Karstensen et al. 2008)

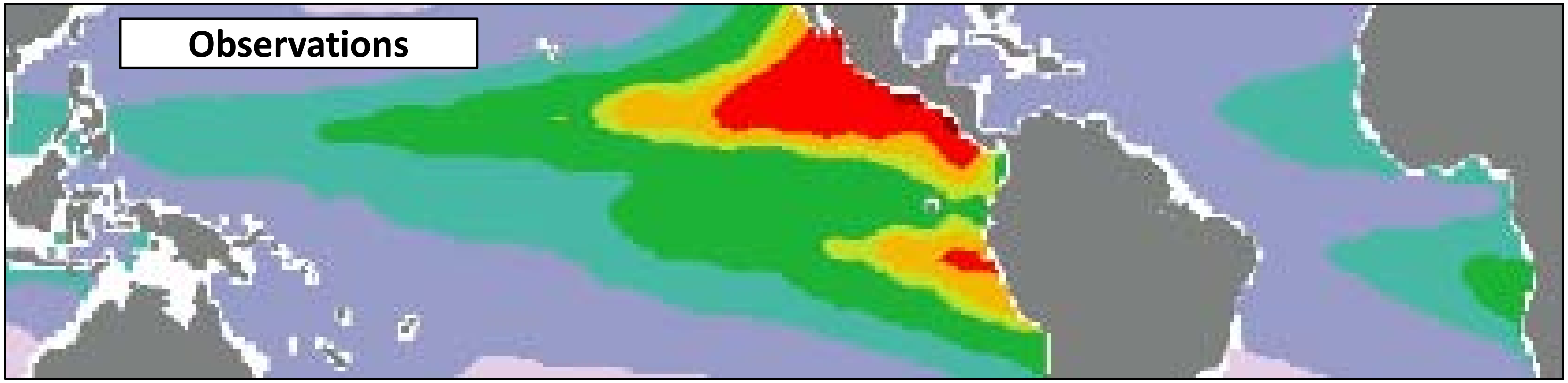


TNEA OMZ Expanding and intensifying

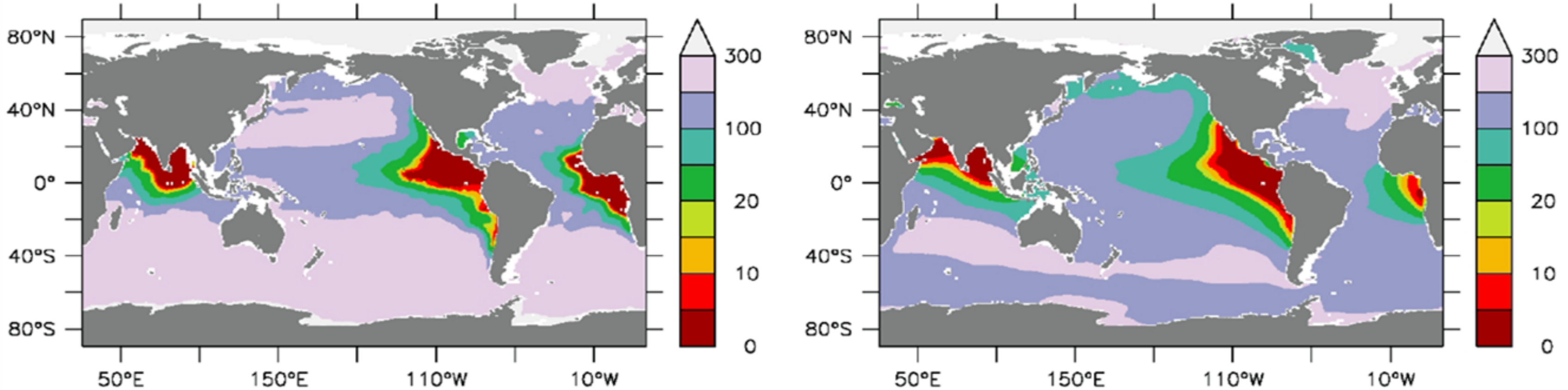
(Stramma et al. 2008)

OMZs in model simulations

State-of-the-art global models not capturing distribution nor levels (300m concentrations, µmol/kg)



WOA

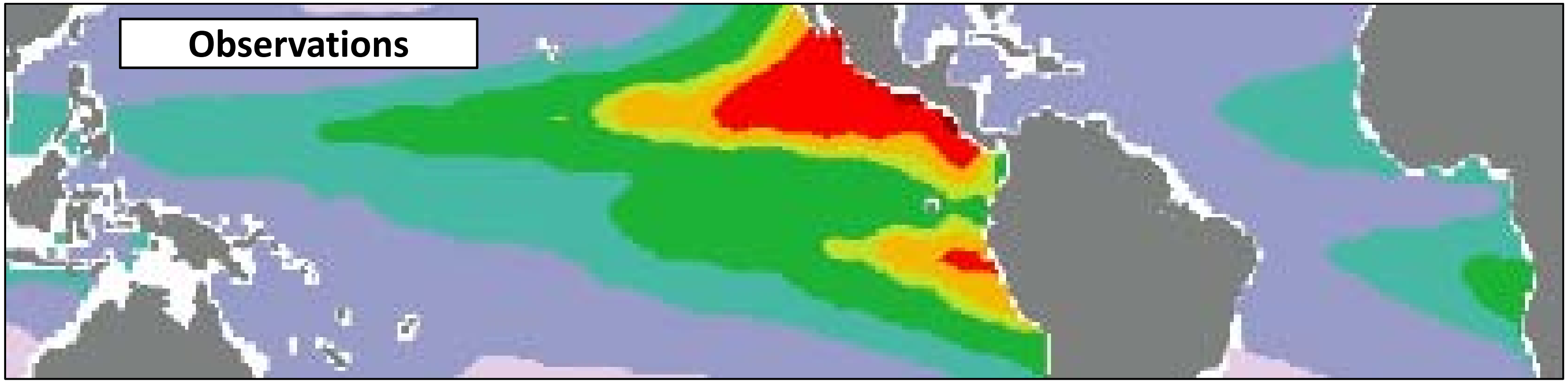


MPIOM *(Max-Planck-Inst. HH)* CCSM *(NCAR)*

Oschlies pers. comm. 2013

OMZs in model simulations

State-of-the-art global models not capturing distribution nor levels (300m concentrations, µmol/kg)



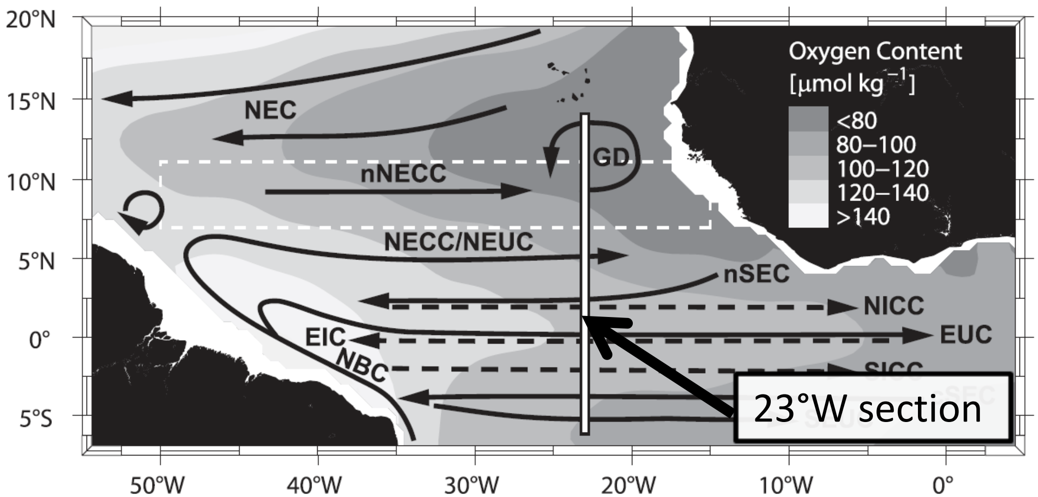
WOA

In order to be able to better prognose future oceanic oxygen developments, It is necessary to understand involved physics and biology, in particular the OMZ response to circulation and ventilation.

SFB 754

(One major scientific question of SFB 754: ‚Climate-Biogeochemistry Interactions in the Tropical Ocean')

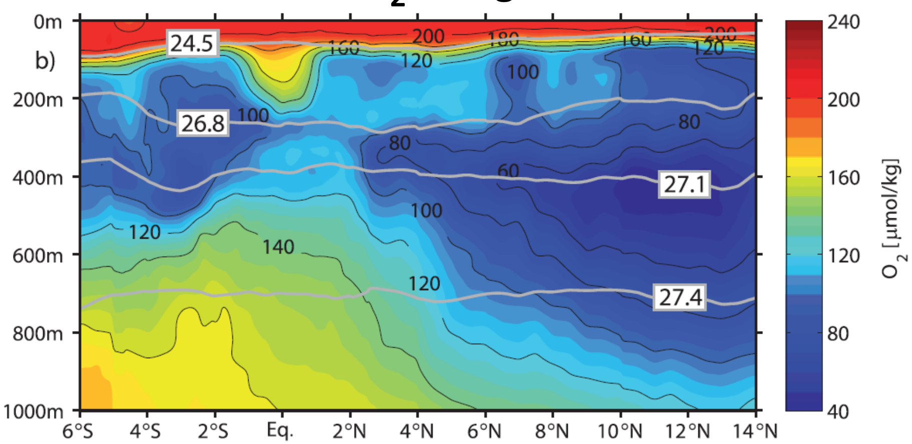
Oxygen Minimum Zone (OMZ) in the Tropical North East Atlantic (TNEA)



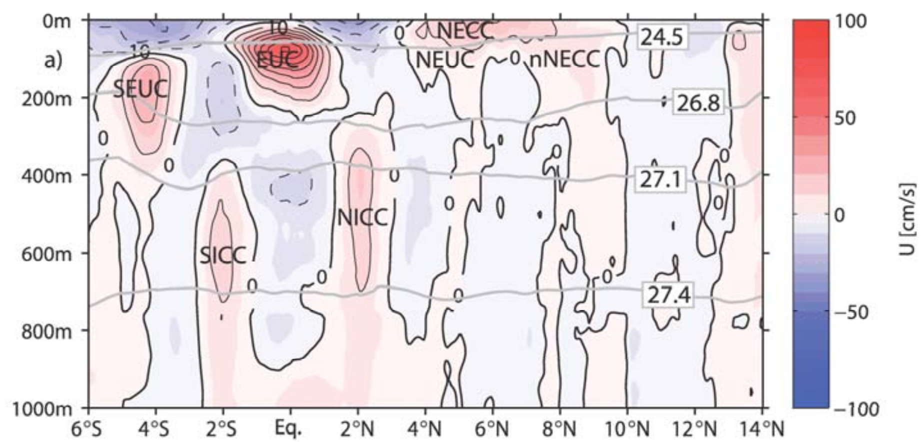
O_2 distribution and equatorial current system (300m - 500m depth)

Brandt et al. (2010)

Mean O_2 along 23W

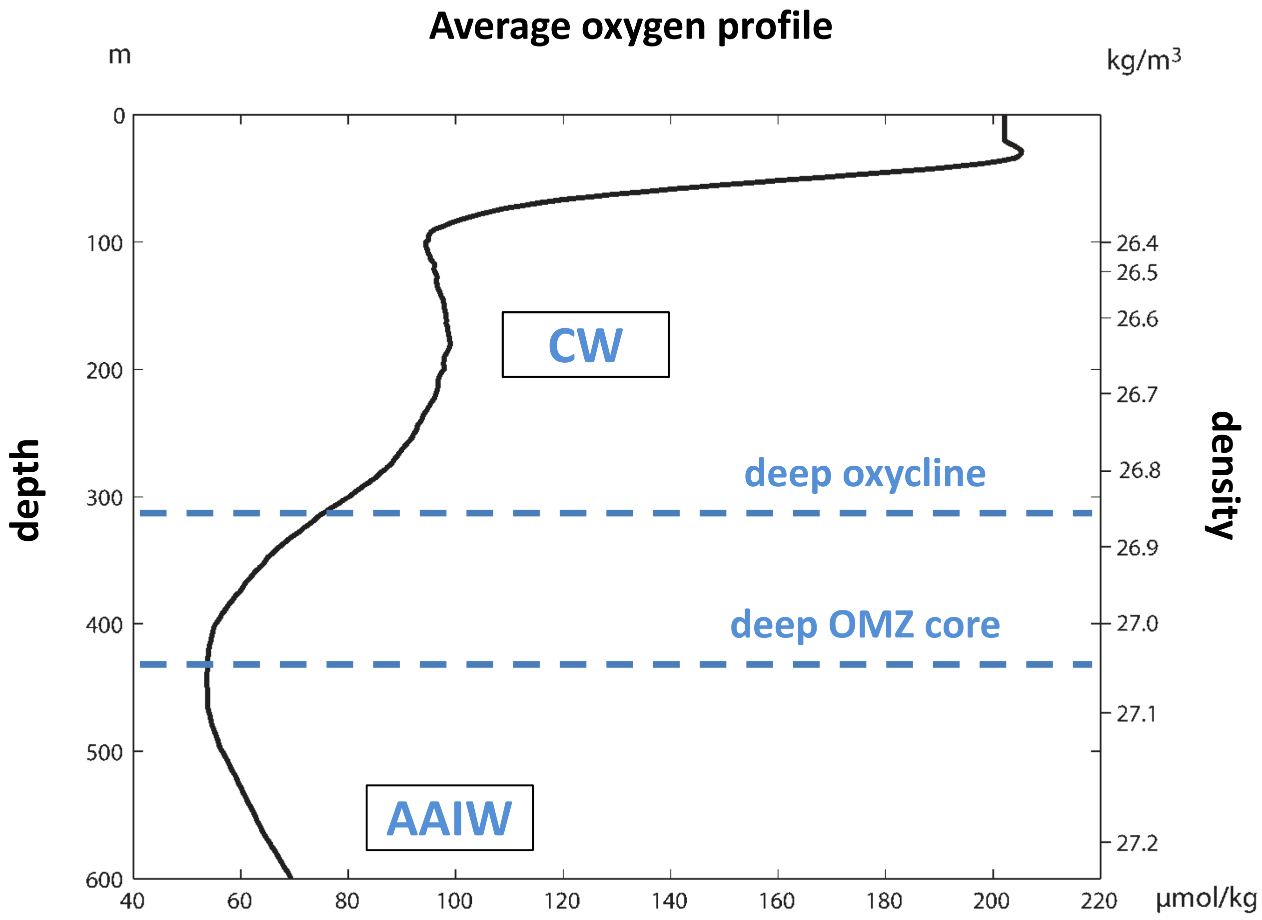


Mean zonal currents



Brandt et al. (2010)

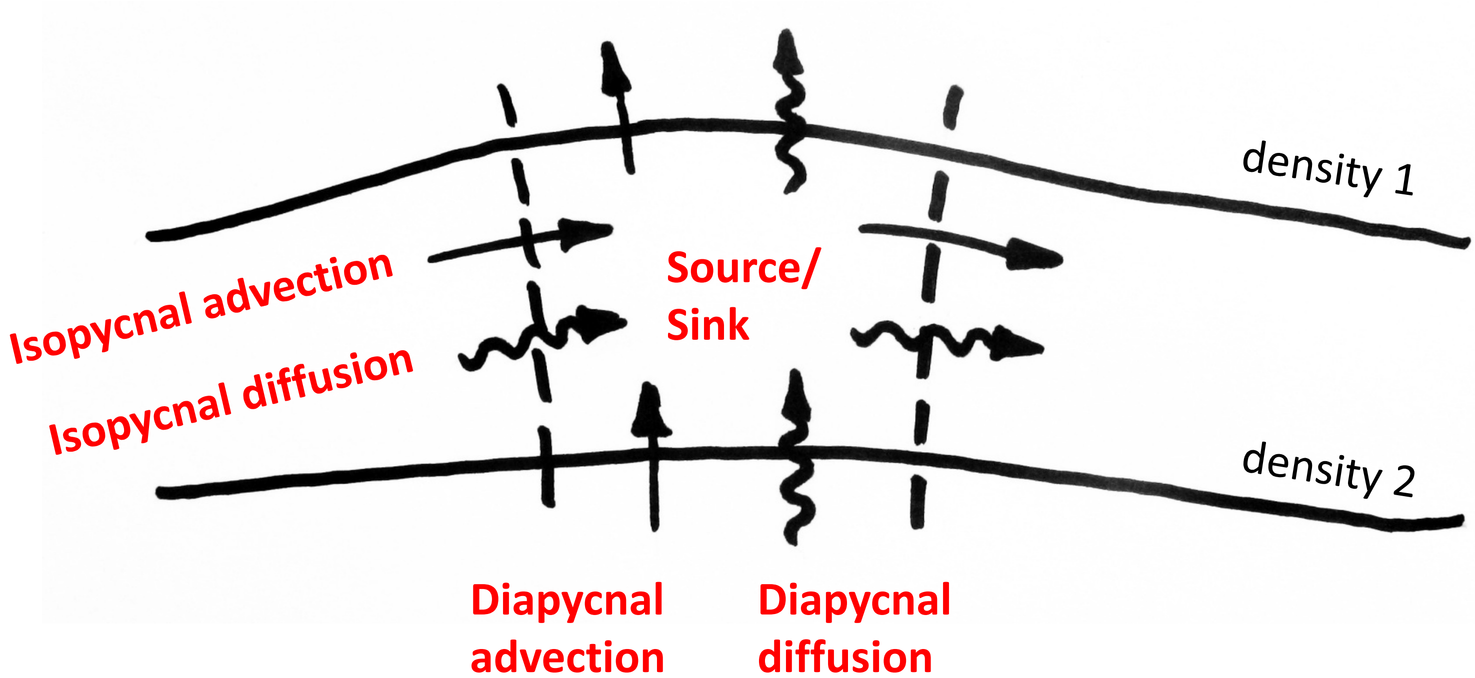
Oxygen Minimum Zone (OMZ) in the Tropical North East Atlantic (TNEA)



CW
Central Water

AAIW
Antarctic Intermediate Water

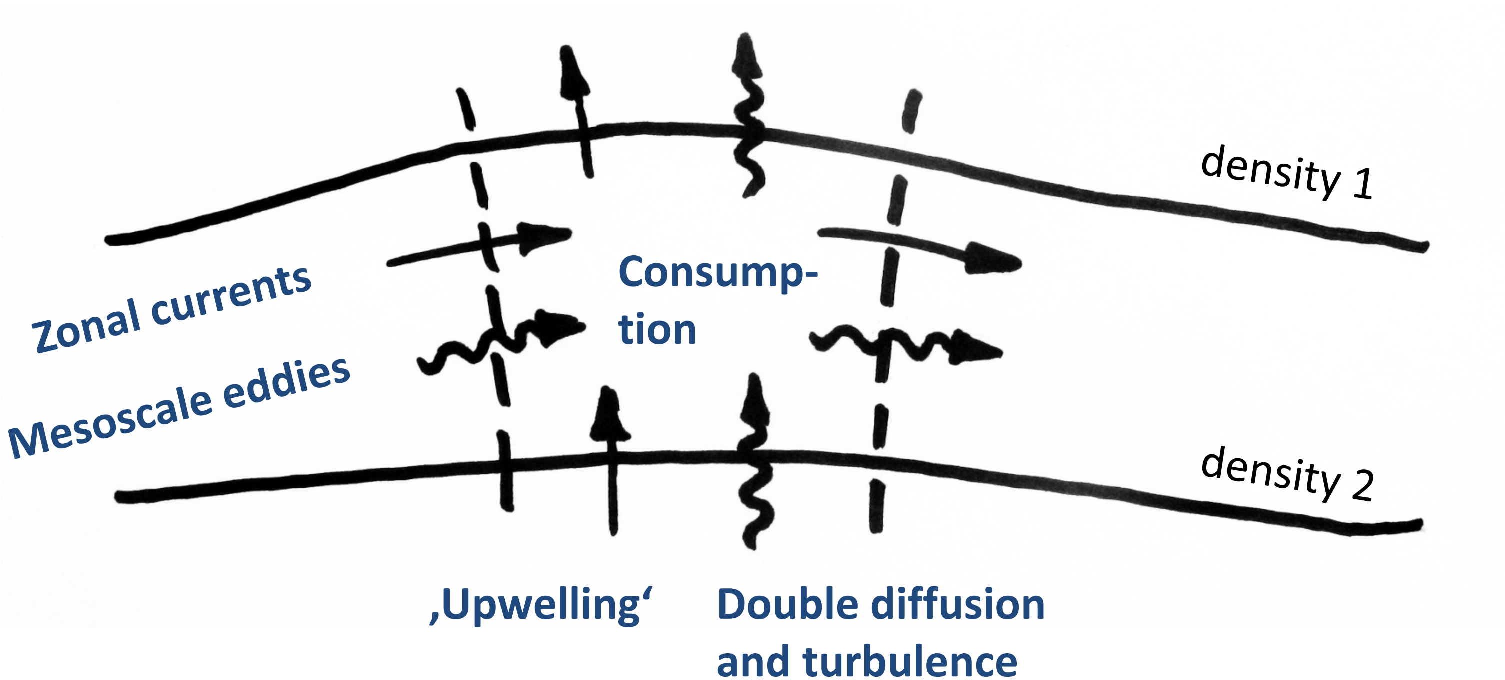
O_2 budget: Processes in density coordinates



Source/sink + isopycnal supply + diapycnal supply* = *tendency/storage

The supply is the difference of fluxes into and out of the volume, i.e. flux divergence

O_2 budget: Processes in density coordinates



Source/sink + isopycnal supply + diapycnal supply** = **tendency/storage

The only important source/sink term in the deep ocean is consumption.

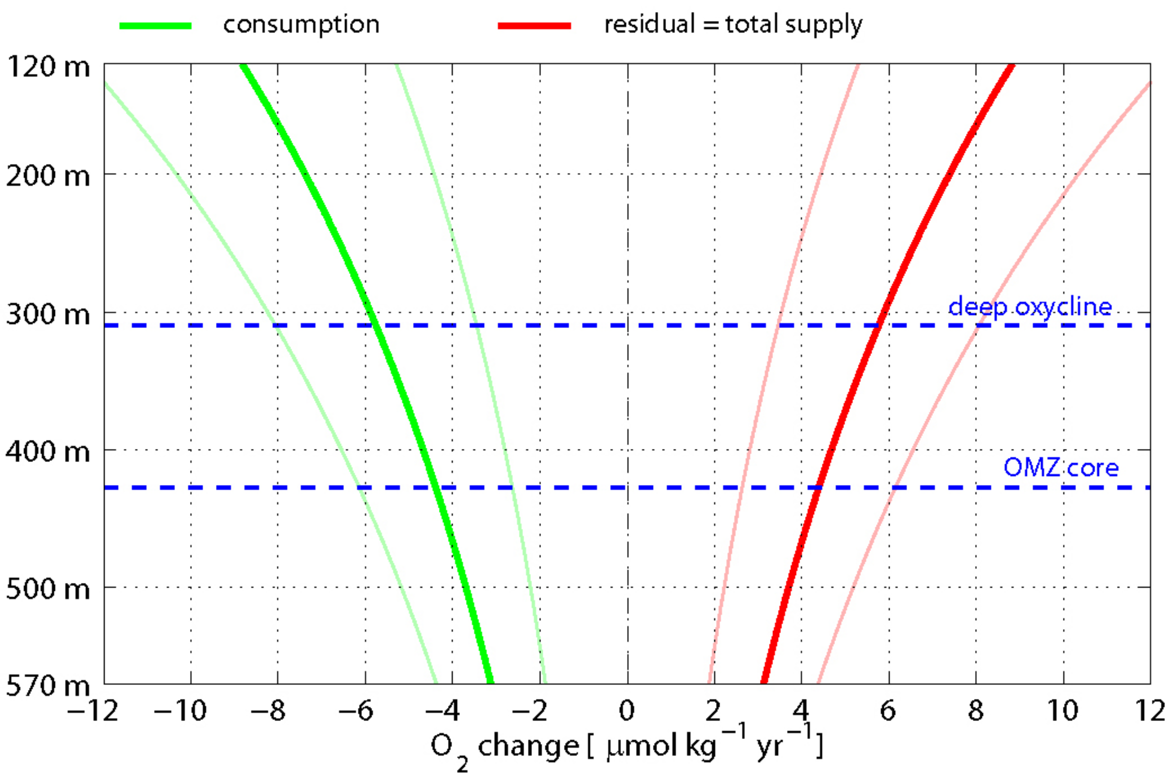
O_2 budget for the TNEA OMZ region (mean profiles of budget terms)

$$\boxed{aOUR \quad + \quad R \quad = \quad 0}$$

Stationarity assumed

consumption
(Karstensen et al., 2008)

residual (total supply)



Quantify some of the missing supply terms

Diapycnal processes

Consumption + isopycnal supply + diapycnal supply = tendency/storage

~~Diapycnal advection~~ + (double diffusion) + turbulent diapycnal diffusion

Estimation method
McDougall 1991

Estimation method
St.Laurent and Schmitt 1999

Diapycnal flux

$$F = -K \cdot \nabla c$$

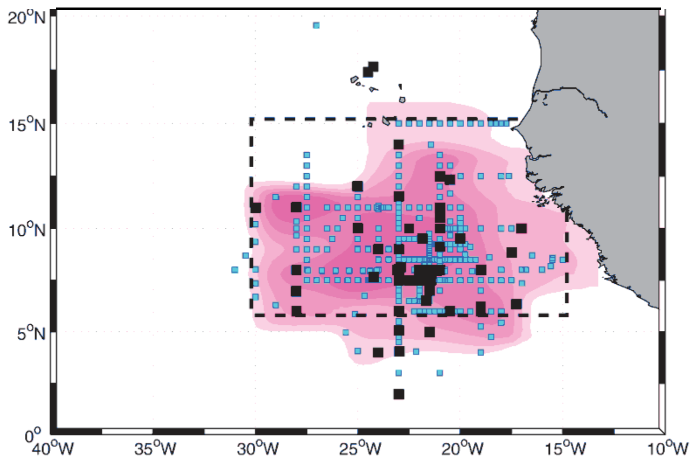
Diapycnal supply to a volume (flux convergence)

$$-\nabla F$$

c	**oxygen concentration**
K	**diapycnal diffusivity**
F	**diapycnal flux**
∇	**diapycnal gradient**

Estimating diapycnal supply requires simultaneous data for K and c

Measurement programme (2008-2010)



- Tracer Release Experiment (TRE)
- Microstructure Profiles (MSS)
- Acoustic Current Profiles (ADCP)
- Oxygen Profiles (CTD-O_2)

Analysis box for this study: 6 to 15 N, 30 to 15 W.

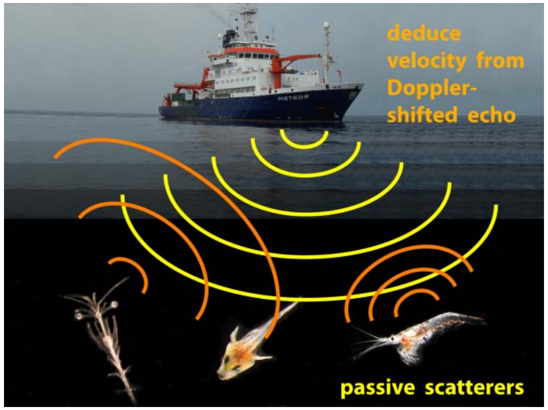
$$K \cdot \nabla c$$

TRE

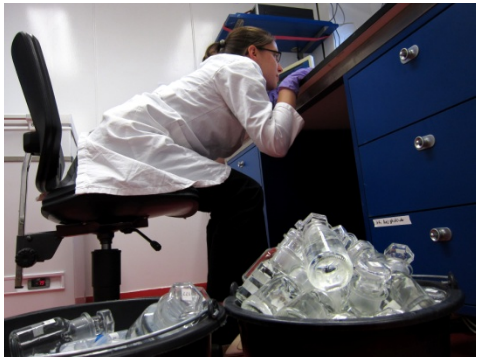
SF_5CF_3

MSS

ADCP



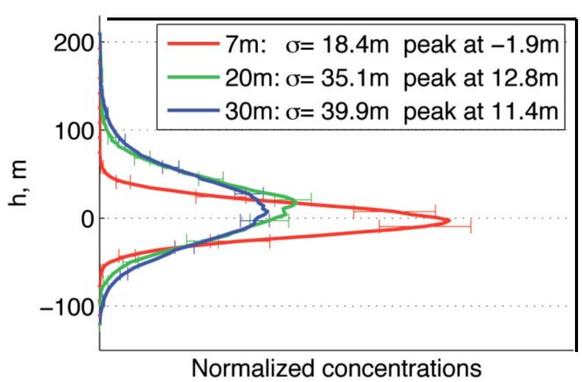
CTD-O_2

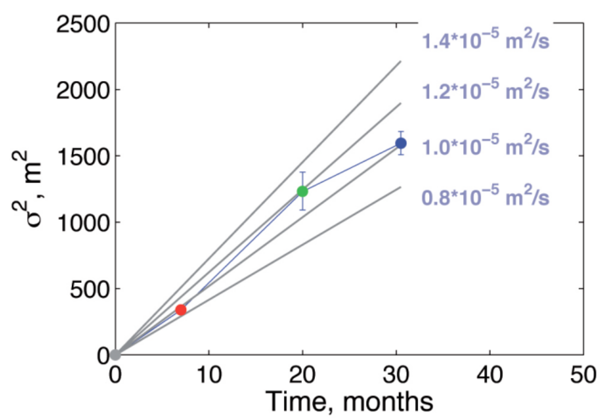


The 3 methods to estimate diapycnal diffusivity K

TRE

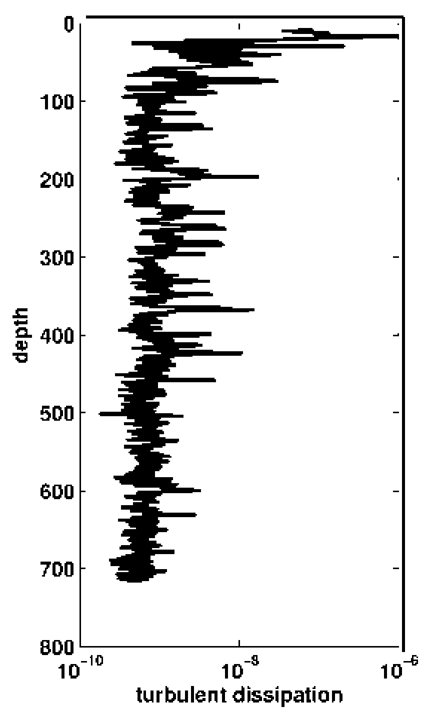
Integrative in space and time.
Only 1 K value. ‚Groundtruthing‘.





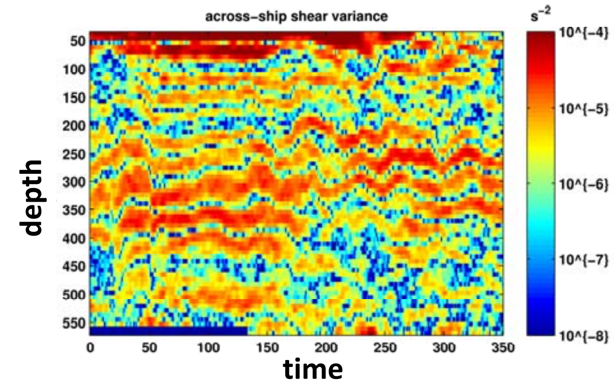
MSS

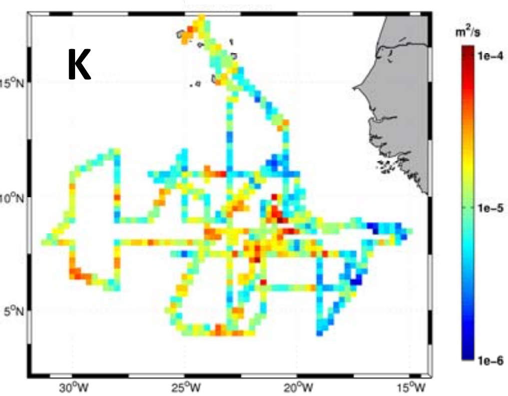
Points in region and time.
Vertical structures.



ADCP

Lines in region and time.
Horizontal structures.





The 3 methods to estimate diapycnal diffusivity K

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MSS

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Vertical structures.

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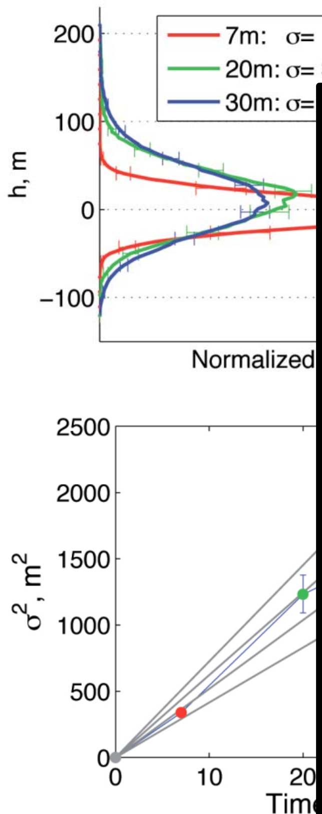
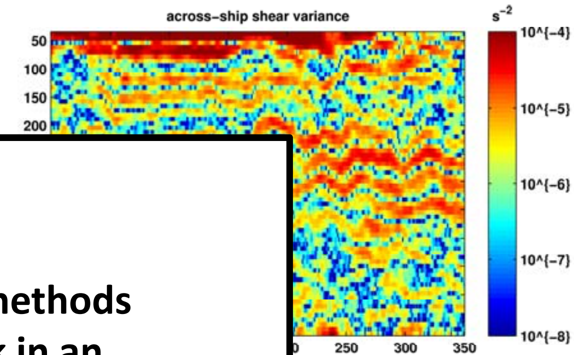
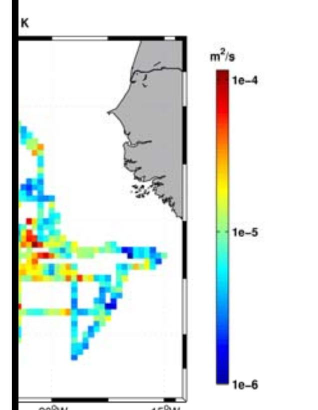
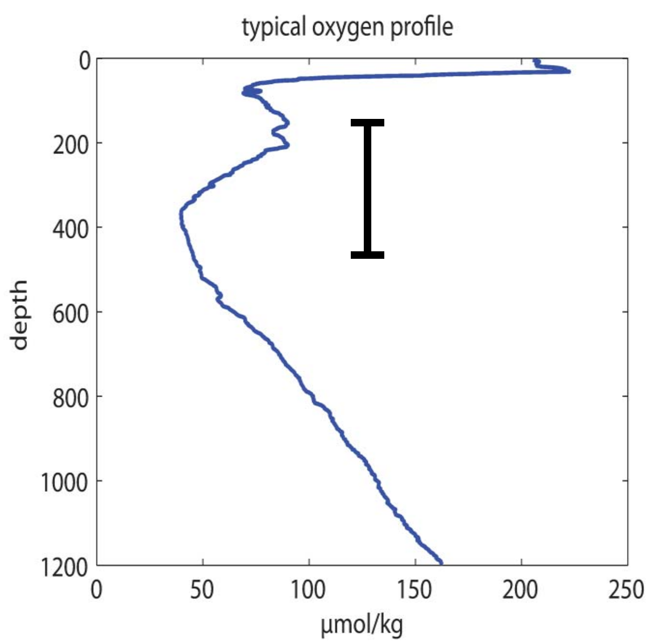
Horizontal structures.





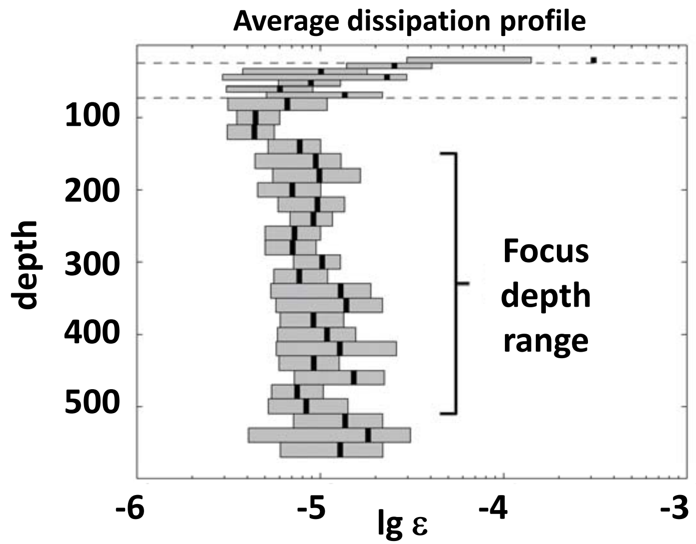




All 3 methods work in an overlapping depth range.

Double diffusion is negligible here.

Diapycnal diffusivity K: intermediate results



$$\langle F\rangle = -\langle K \cdot \nabla c\rangle = -\langle K\rangle \cdot \langle \nabla c\rangle$$

$$\langle K\rangle_{TRE} = (1.2 \pm 0.2) \cdot 10^{-5}\ \frac{m^2}{s}$$

$$\langle K\rangle_{MSS,ADCP} = (1.0 \pm 0.2) \cdot 10^{-5}\ \frac{m^2}{s}$$

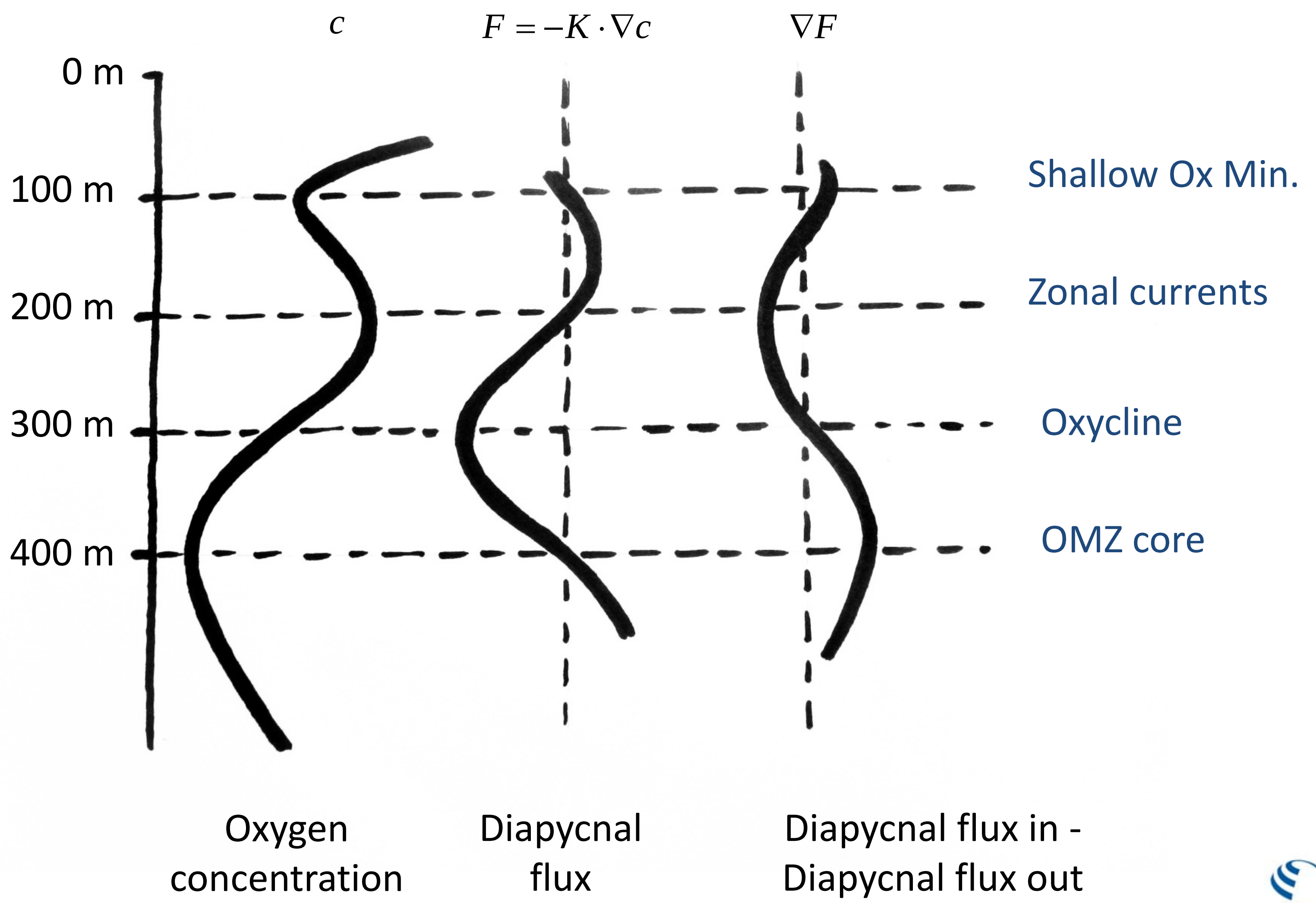
MSS: K is approximately constant with depth in the focus depth range 150 – 500m

K and gradient c are independent in each depth layer.
The two properties simplify the merging of the 3 methods.

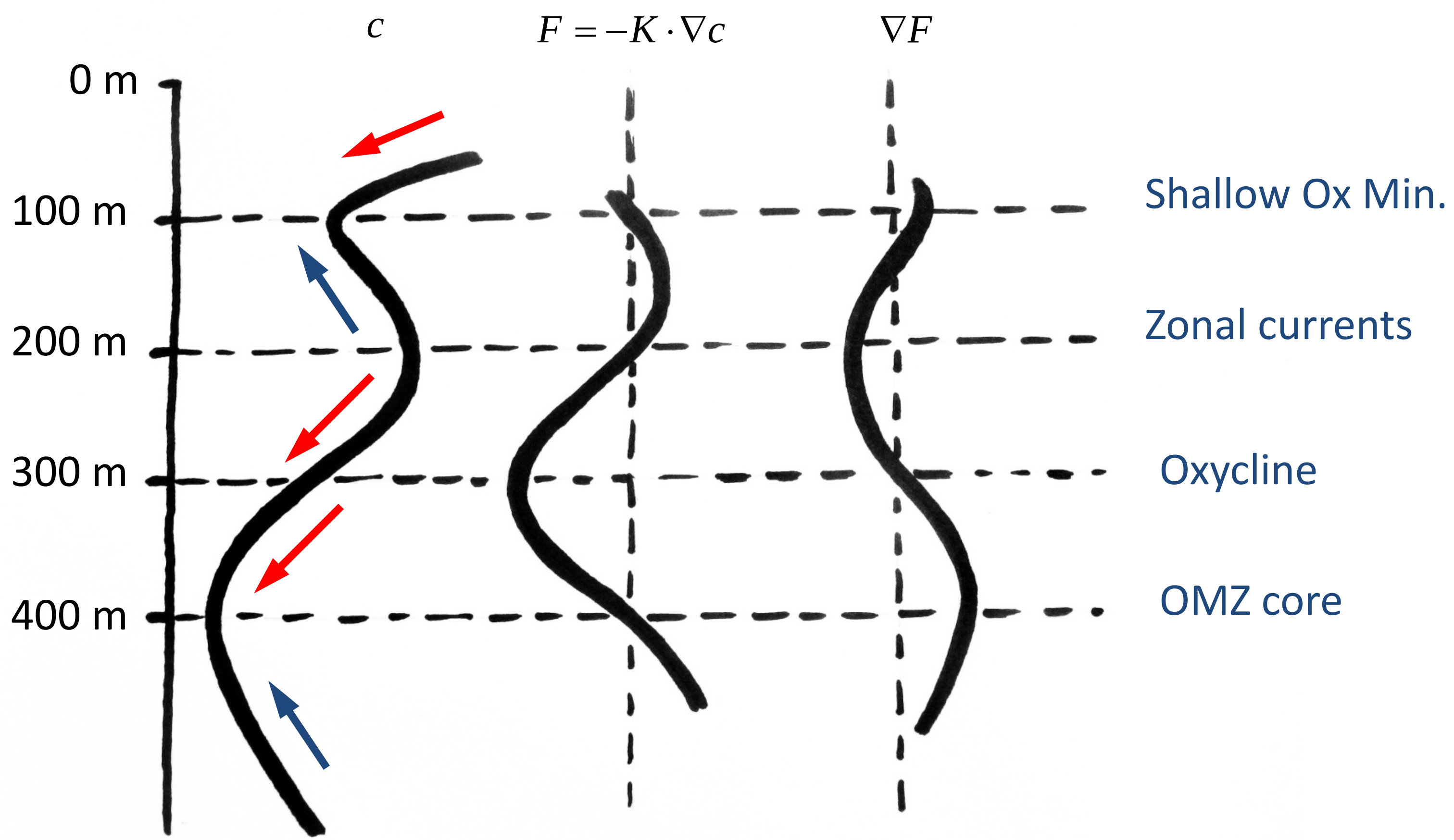
K from TRE and from MSS/ADCP agree in uncertainty limits

K is substantially stronger than the expected background value

Concentration : flux : supply



Concentration : flux : supply

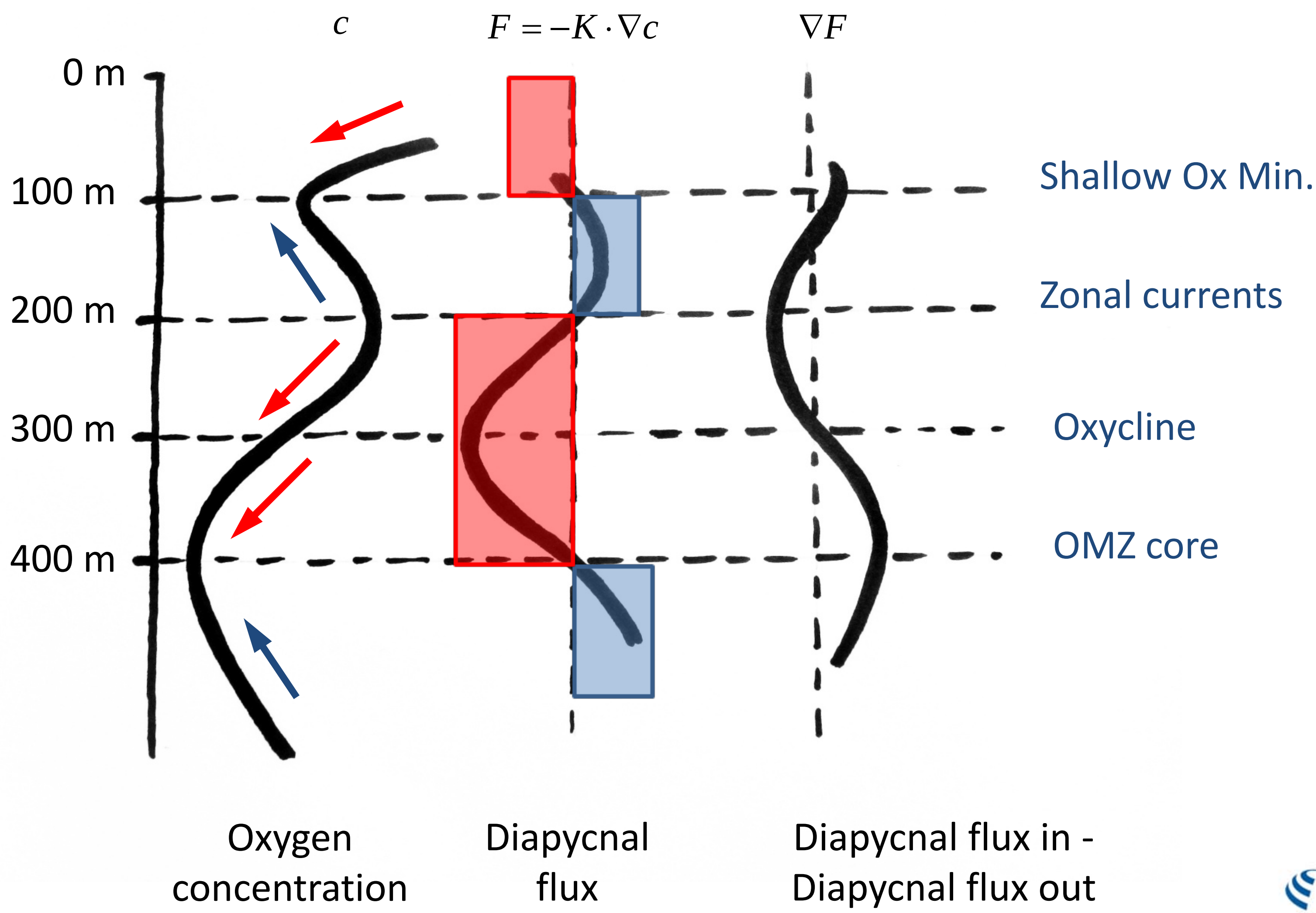


Oxygen concentration

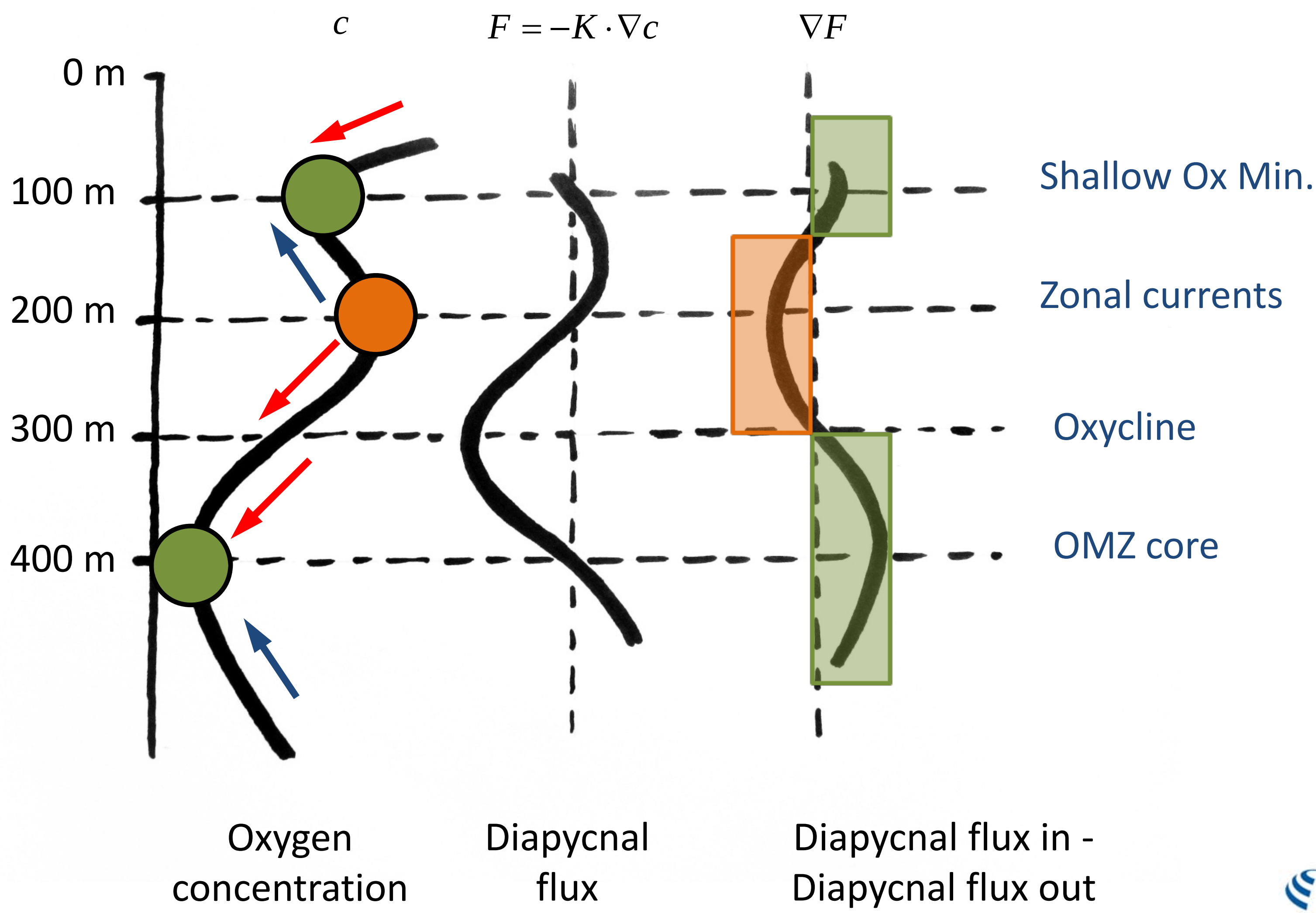
Diapycnal flux

Diapycnal flux in - Diapycnal flux out

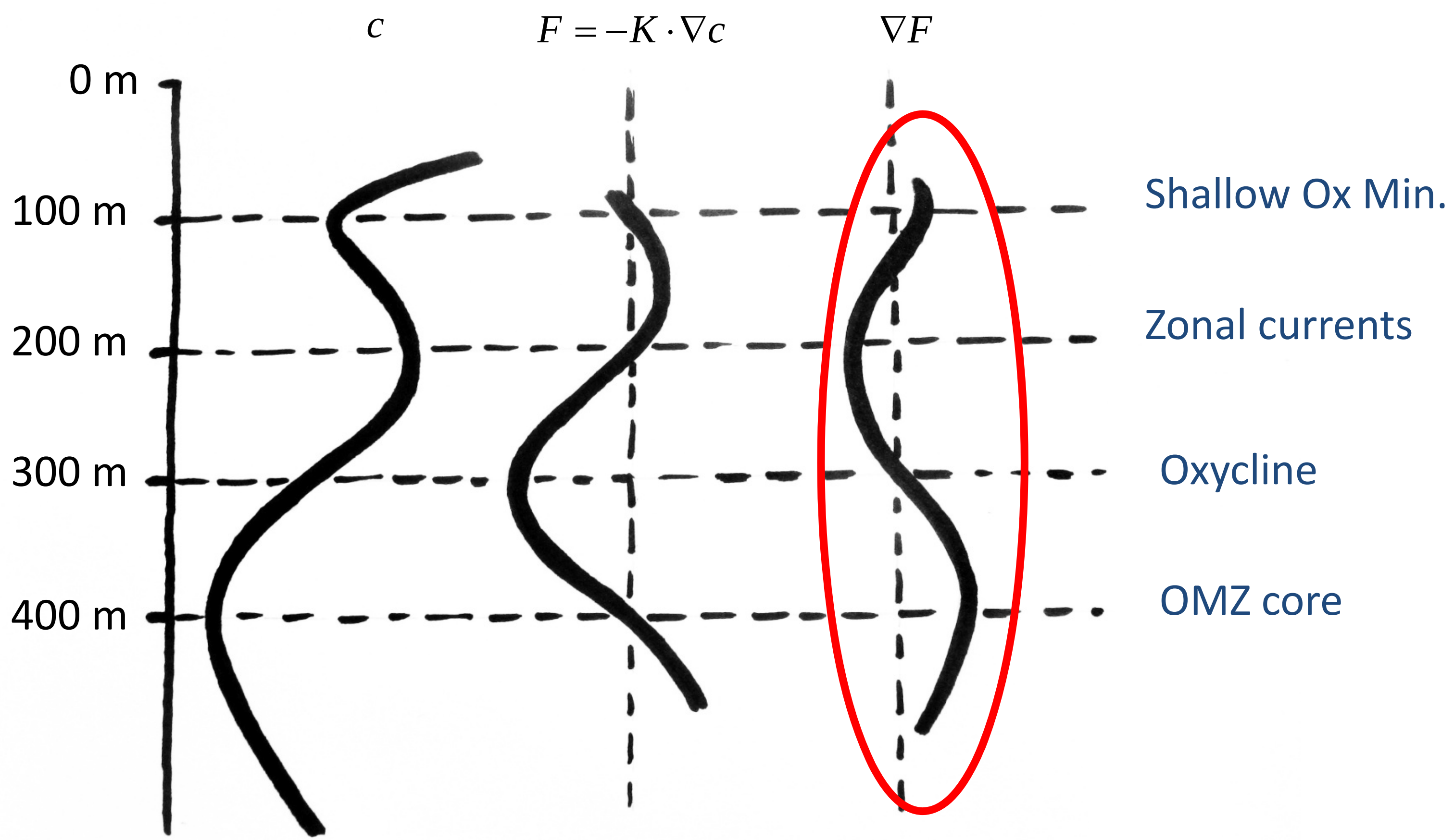
Concentration : flux : supply



Concentration : flux : supply



Concentration : flux : supply



Oxygen concentration

Diapycnal flux

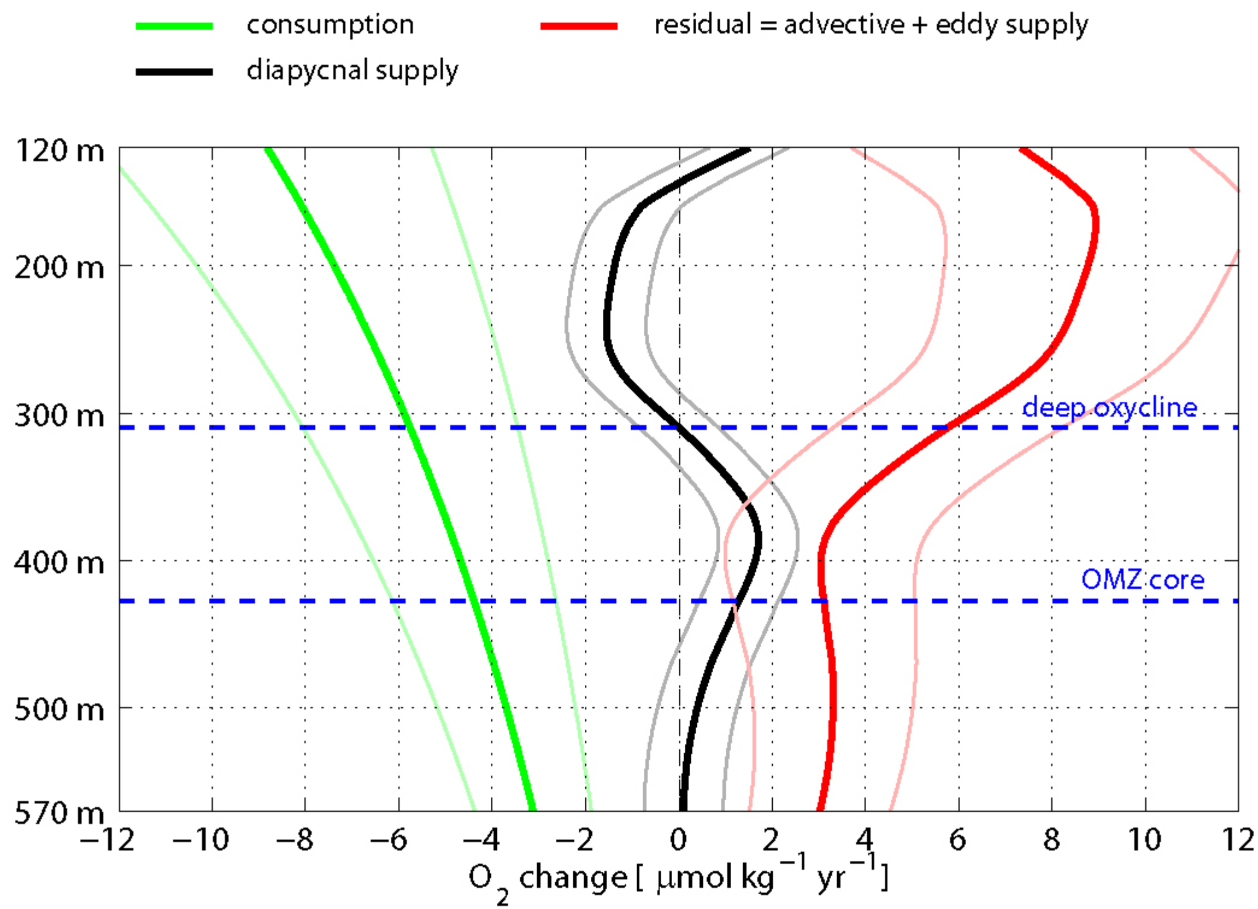
Diapycnal flux in - Diapycnal flux out

O_2 budget

$$\boxed{aOUR + O_{2,dia} + R^{(1)} = 0}$$

Stationarity assumed

consumption *(Karstensen et al., 2008)* | ***diapycnal supply*** | ***Isopycnal residual (advective + eddy supply)***



Fischer et al. 2013

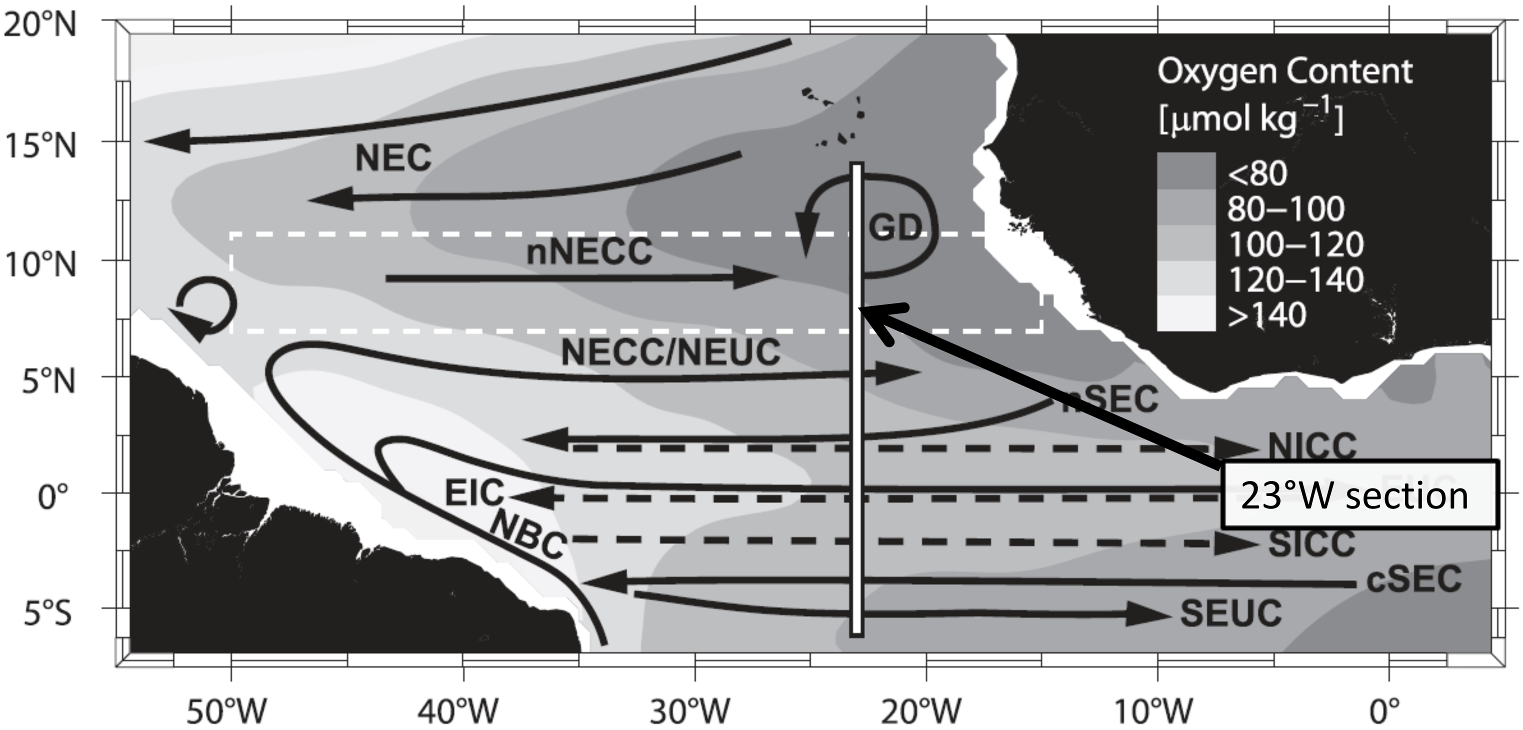
1. The Oxygen Minimum Zone of the Tropical North East Atlantic (TNEA OMZ)

2. Diapycnal Oxygen Supply

3. **Eddy-Driven Meridional Oxygen Supply**
   - 3.1 Flux Gradient Parameterization
   - 3.2 Time Series Correlation
   - 3.3 Oxygen Flux Divergence

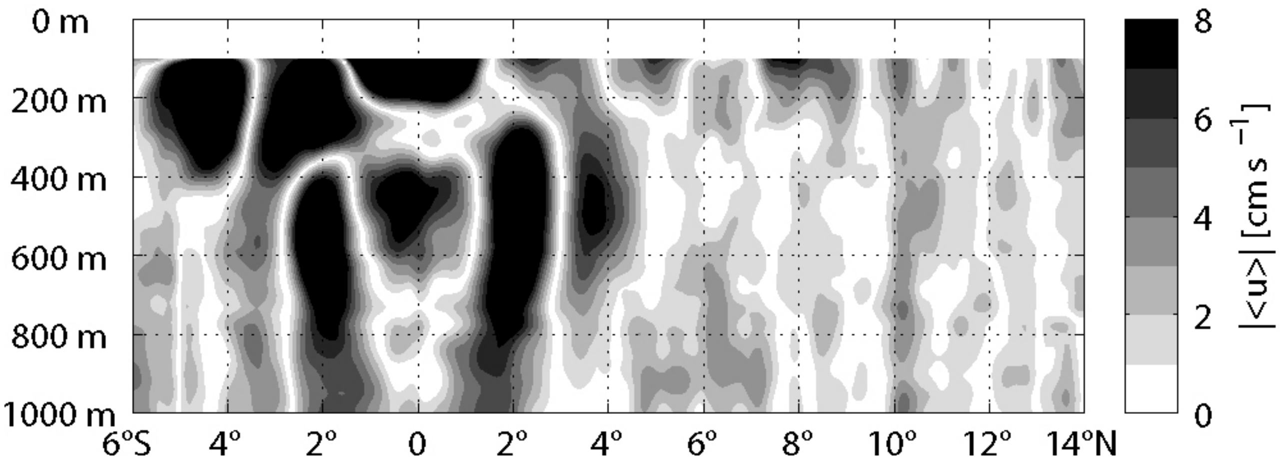
4. **Summary and Outlook**

Characteristic section cutting through the OMZ of the TNEA

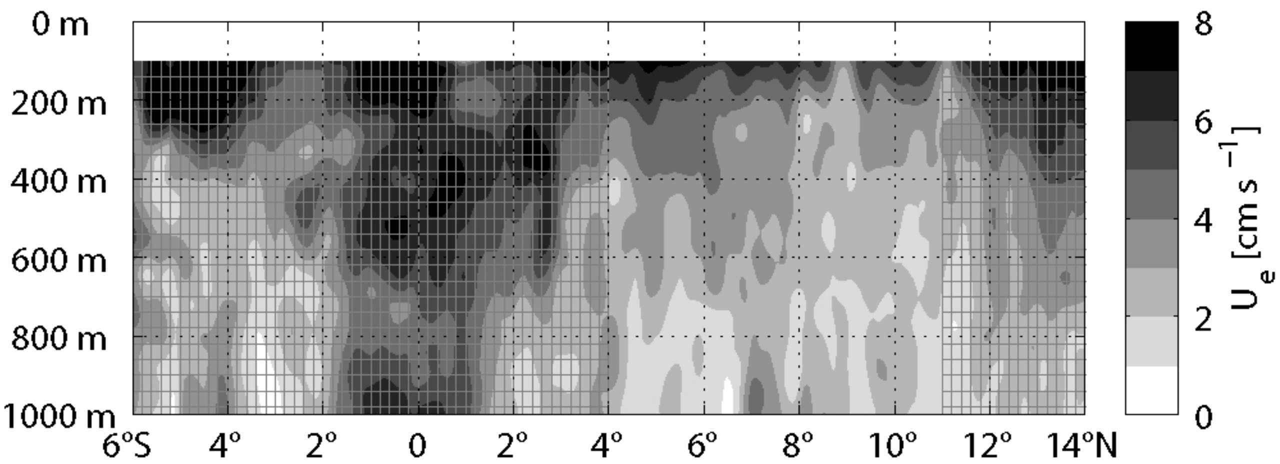


Brandt et al. (2010)

Zonal mean and mesoscale velocity along 23°W



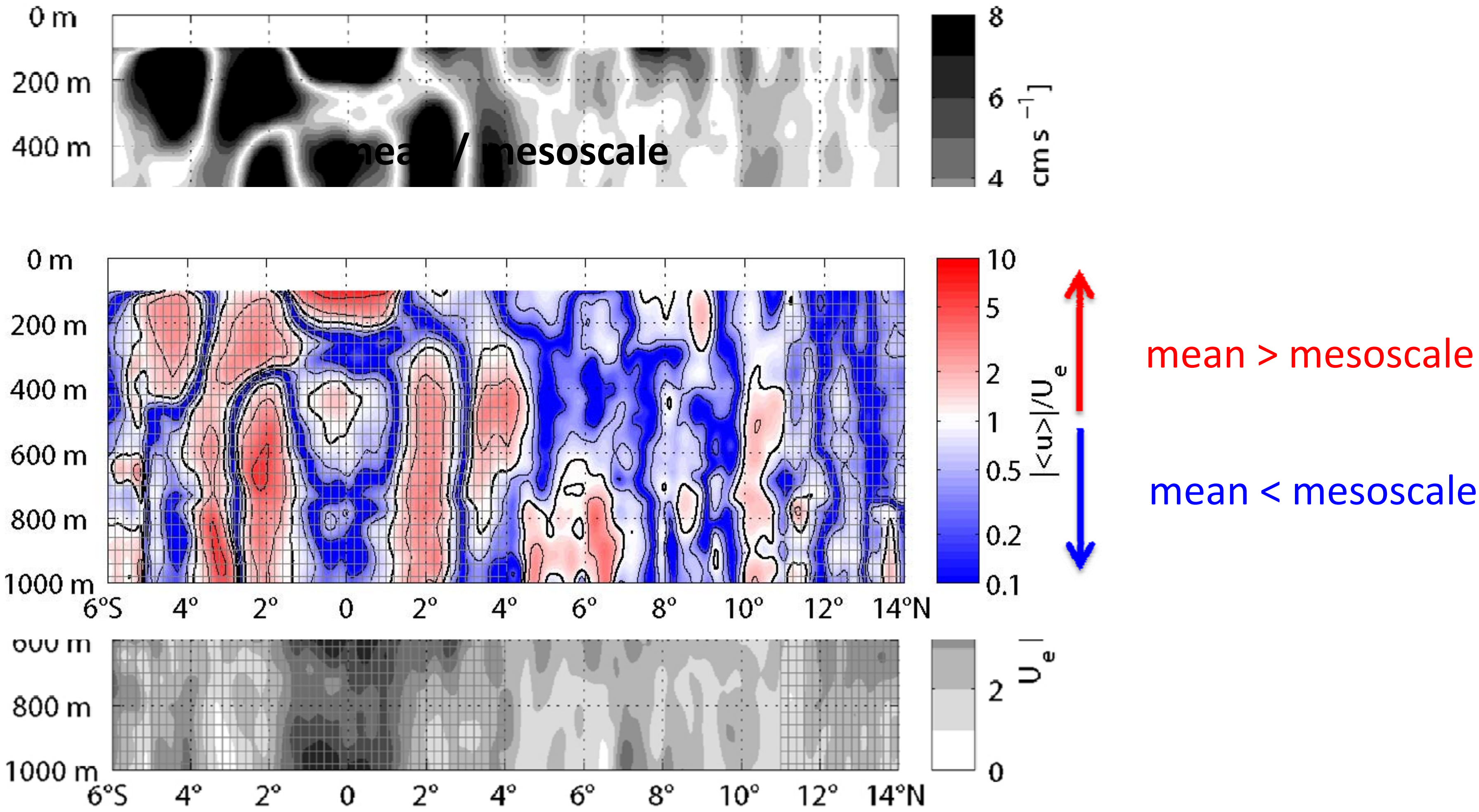
mean, |<*u*>|



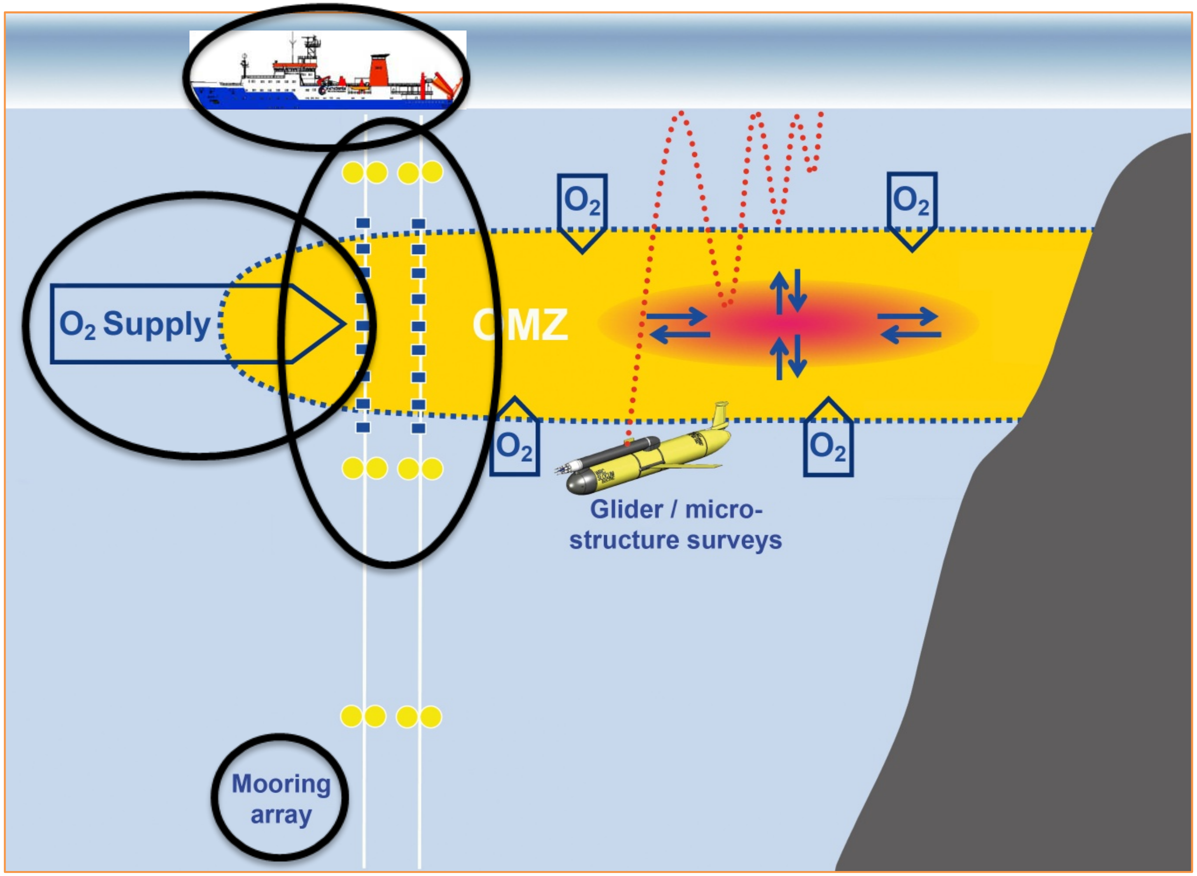
mesoscale,

$$U_e = \sqrt{EKE} = \sqrt{(u'^2 + v'^2)/2}$$

Zonal mean and mesoscale velocity along 23°W



Eddy-driven meridional O_2 Flux



Two methods

(I) Flux gradient parameterization

→ analysis based on repeated ship sections

$$F = -K_e \frac{dO_2}{dy}$$

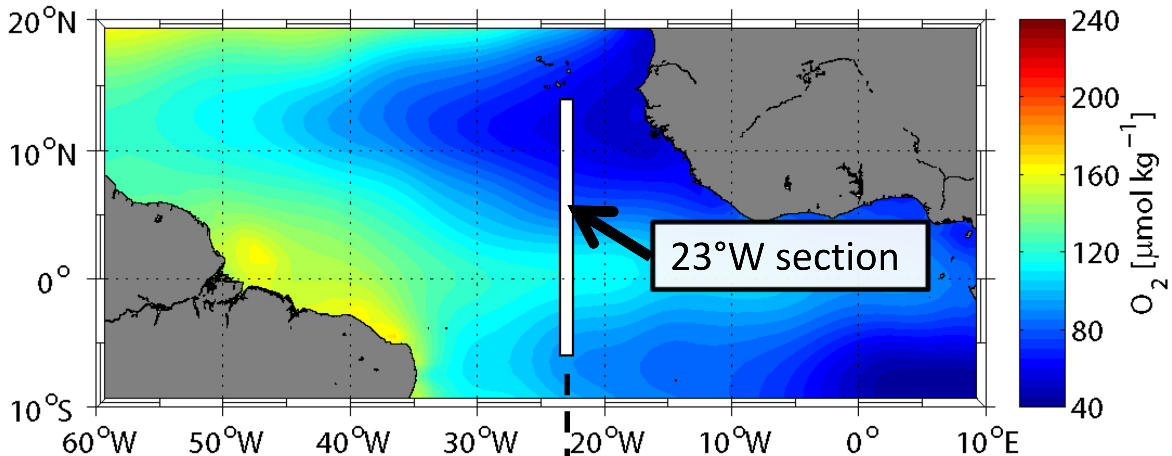
(II) Correlation method

→ analysis based on mooring time series

$$F = \langle v' O_2' \rangle$$

SFB 754, proposal 2nd phase, 2011

1.Repeated ship sections along 23°W (1999 - 2011)



background: O_2 distribution at 400m depth from *World Ocean Atlas 2009*

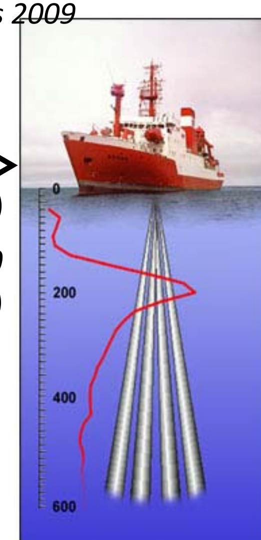
photo: A. Krupke

(I) Hydrography (CTD/O_2)

average # cruises = 8
(> 500 profiles in upper 1000m)

(II) Velocity (ADCP)

average # cruises = 10
(for depth range > 700m)



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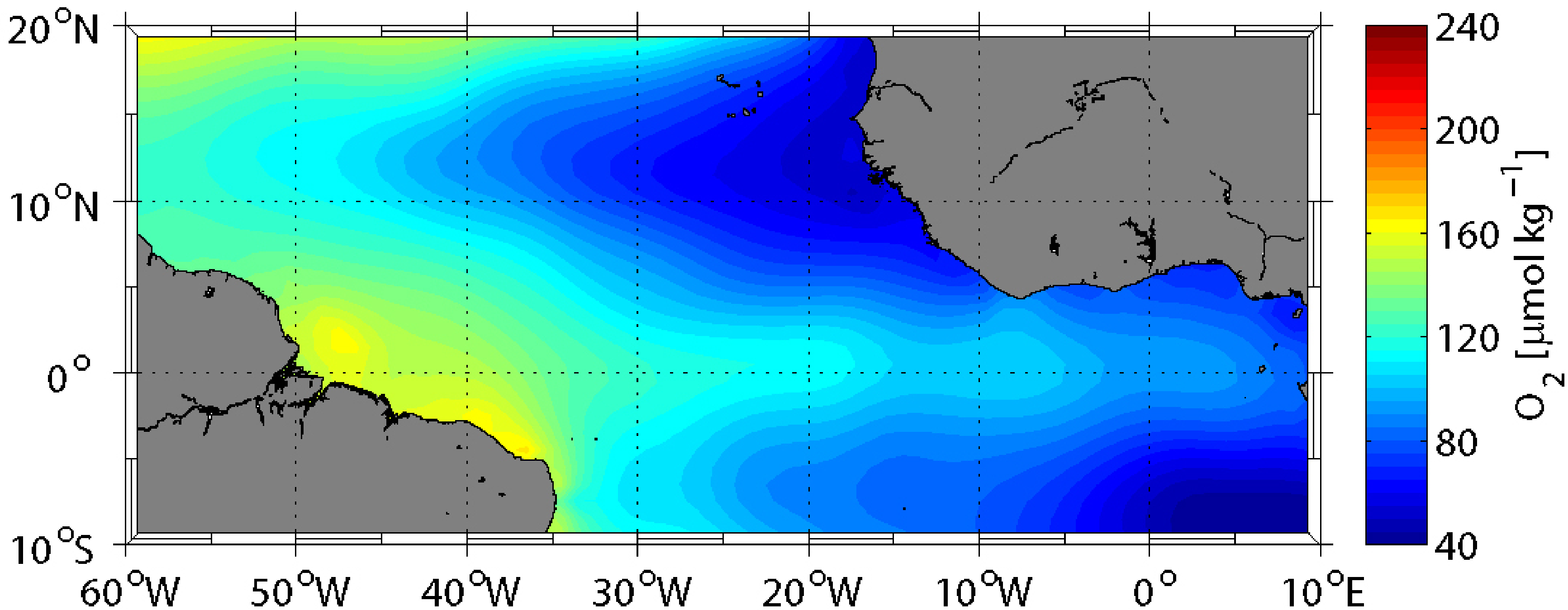
2. Climatological data – World Ocean Atlas 2009

⇨ annual mean hydrography of the Tropical Atlantic



O_2 distribution at 400m depth from *World Ocean Atlas 2009*

Goal: estimate a mean K_e profile

… to estimate eddy-driven meridional O_2 flux

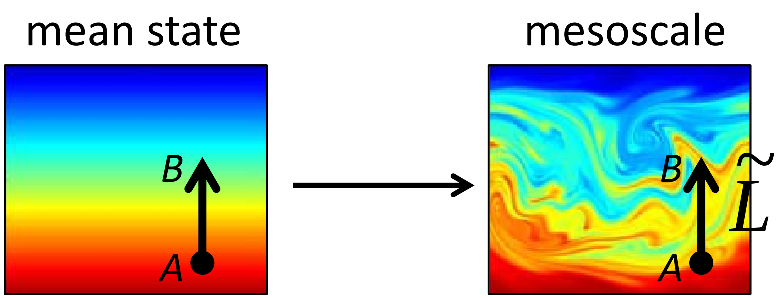
$$F = -K_e \frac{dO_2}{dy}$$

Goal: estimate a mean K_e profile

Basic approach:

$$\boxed{K_e \propto U_e \tilde{L}}$$

$\tilde{L}$ … characteristic eddy length scale



U_e … characteristic eddy velocity

$$U_e = \sqrt{EKE} = \sqrt{(u'^2 + v'^2)/2}$$

Goal: estimate a mean K_e profile

1. Mixing length theory

(Armi and Stommel (1983), Ferrari and Polzin (2005))

$$\boxed{K_e = c_e U_e L_e}$$

$$L_e = {O_2'}\big/{\left|\nabla_\sigma O_2\right|}$$

$$U_e = \sqrt{EKE} = \sqrt{(u'^2 + v'^2)/2}$$

$$c_e = 0.16$$

2. Rhines scale *(Eden, 2007)*

$$\boxed{K_e \propto U_e L_R}$$

$$L_R = \sqrt{{U_e}\big/{2\beta}}$$

$$U_e = \sqrt{EKE} = \sqrt{(u'^2 + v'^2)/2}$$

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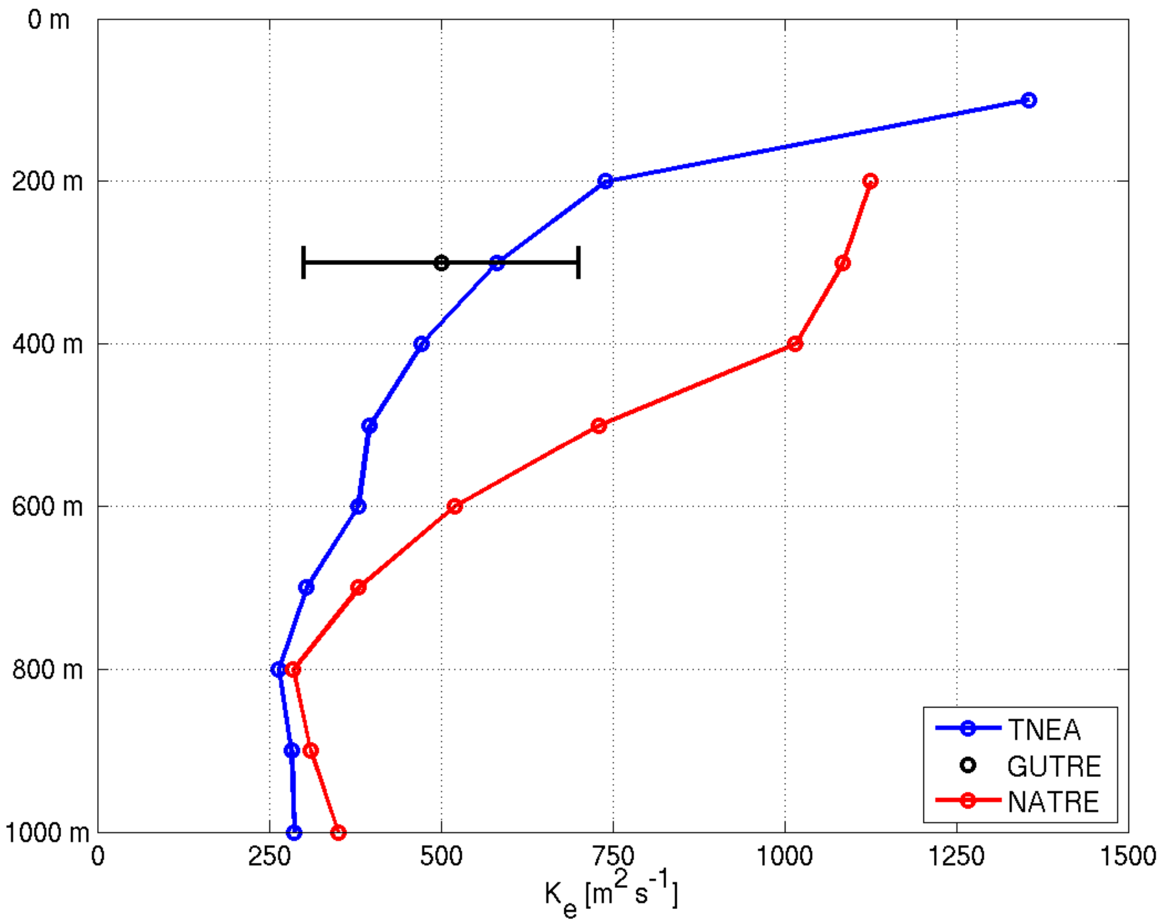
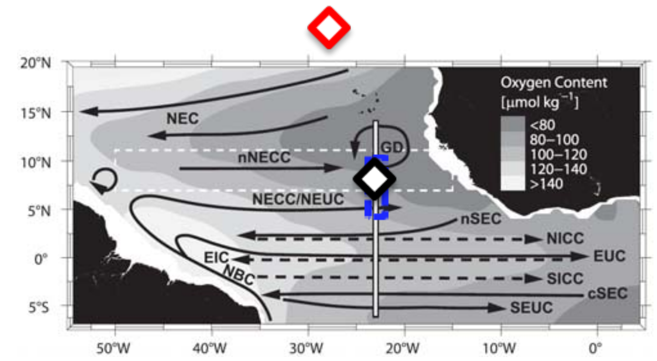
mean K_e profile





Brandt et al. (2010)

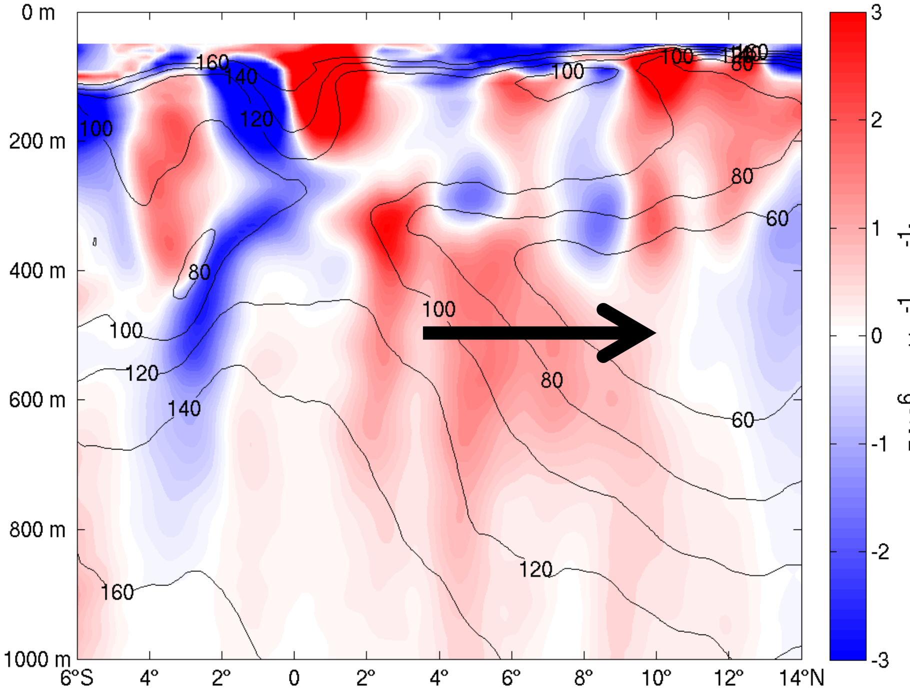
TNEA: *Hahn et al. (subm.)*

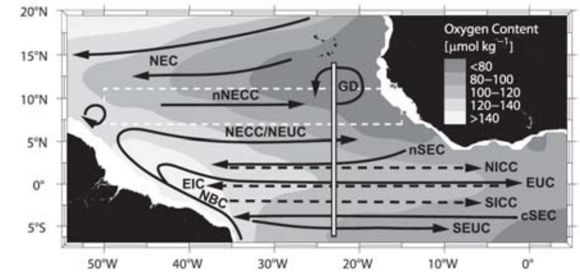
GUTRE: *Banyte et al. (2013)*

NATRE: *Ferrari and Polzin (2005)*

Eddy-Driven Meridional O_2 flux along 23°W

(I) $$F = -K_e \frac{dO_2}{dy}$$





Brandt et al. (2010)

northward O_2 flux

southward O_2 flux

northward O_2 flux at 400m-600m

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1. The Oxygen Minimum Zone of the Tropical North East Atlantic (TNEA OMZ)

2. Diapycnal Oxygen Supply

3. **Eddy-Driven Meridional Oxygen Supply**

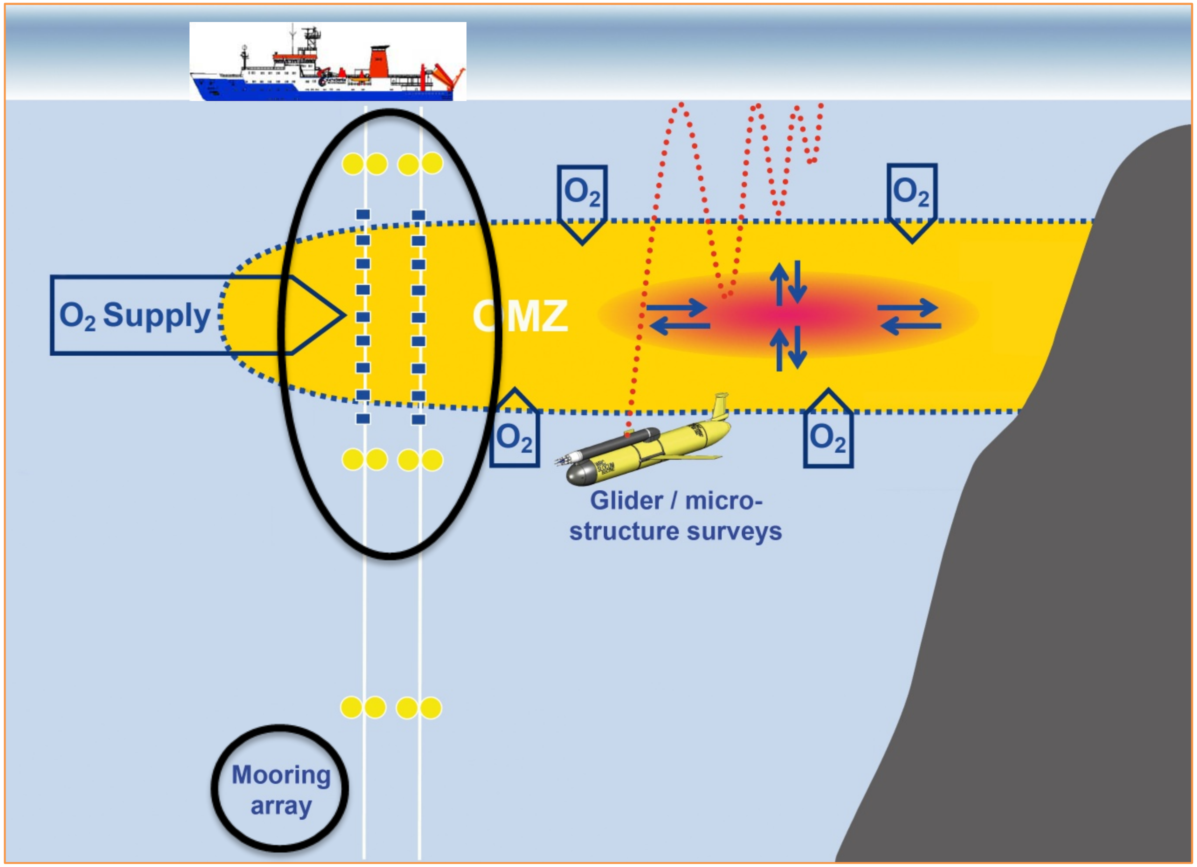
   3.1 Flux Gradient Parameterization

   3.2 **Time Series Correlation**

   3.3 **Oxygen Flux Divergence**

4. **Summary and Outlook**

Eddy-driven meridional O_2 Flux



Two methods

(I) Flux gradient parameterization

→ analysis based on repeated ship sections

$$F = -K_e \frac{dO_2}{dy}$$

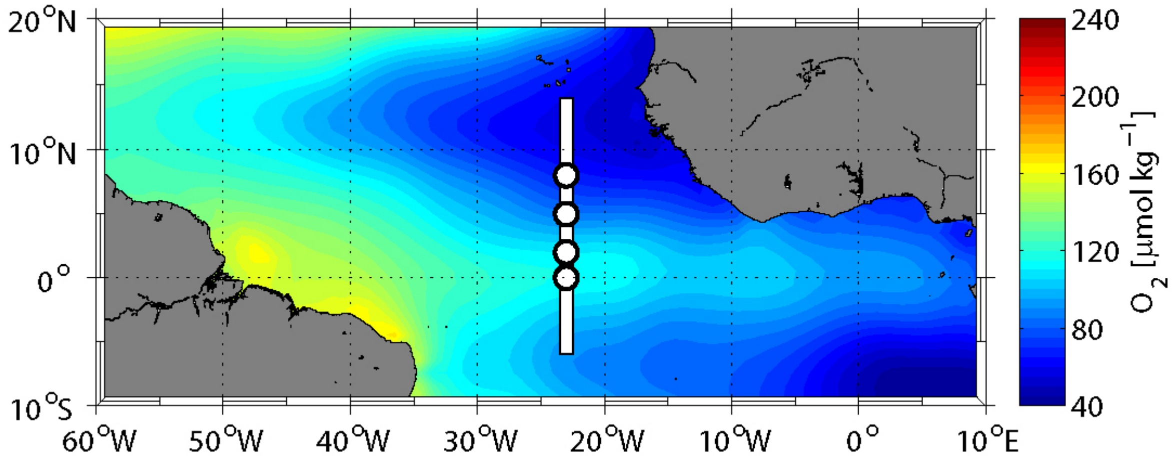
(II) Correlation method

→ analysis based on mooring time series

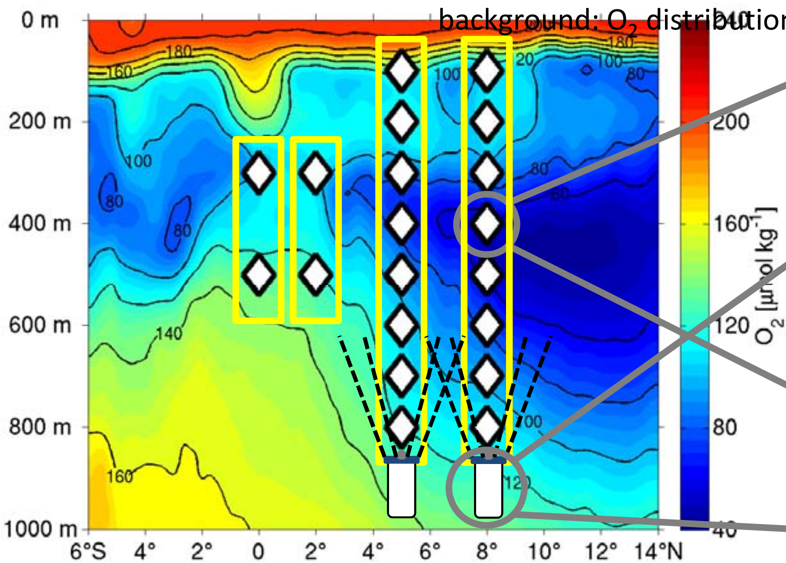
$$F = \langle v' O_2' \rangle$$

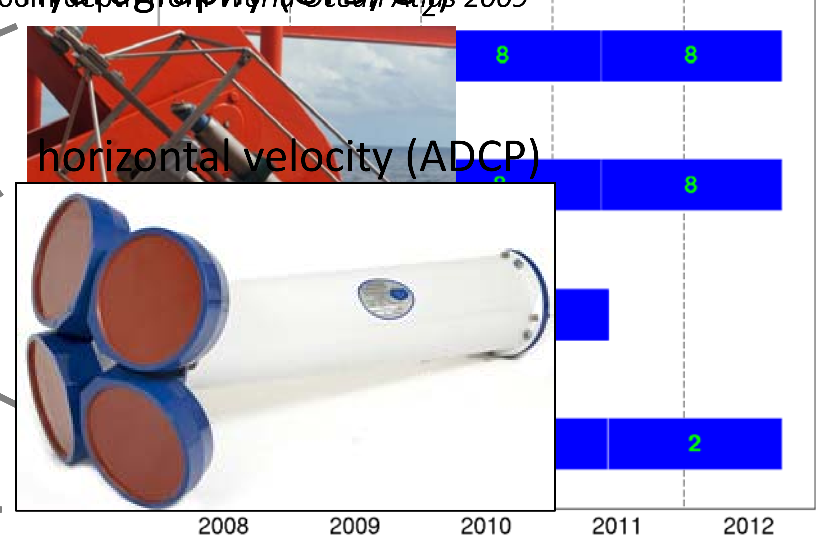
SFB 754, proposal 2nd phase, 2011

Moored observations along 23°W



background: O_2 distribution at 400m depth from *World Ocean Atlas 2009*





Moored observations along 23°W
(O_2 distribution: update from *Brandt et al. (2010)*)

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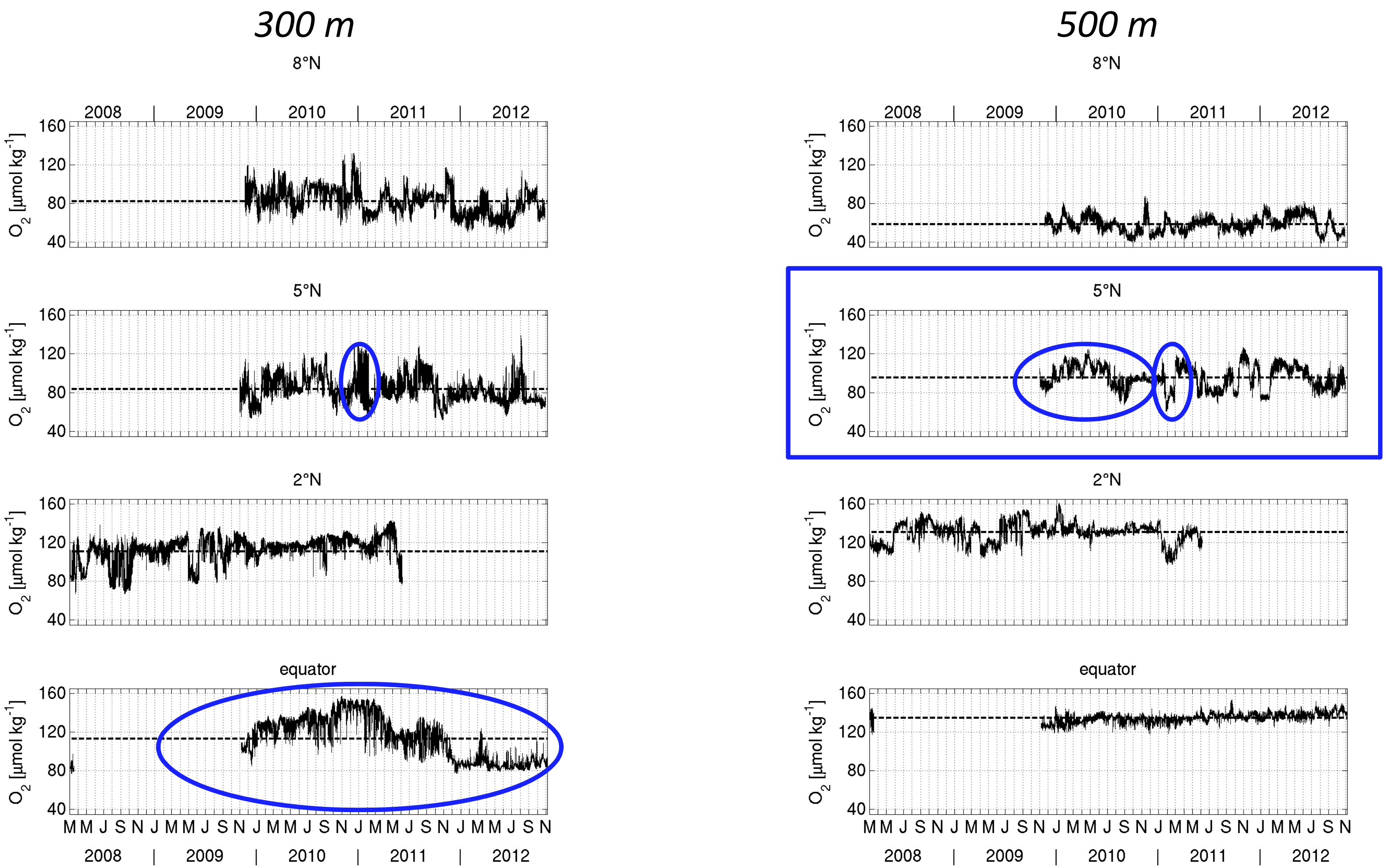
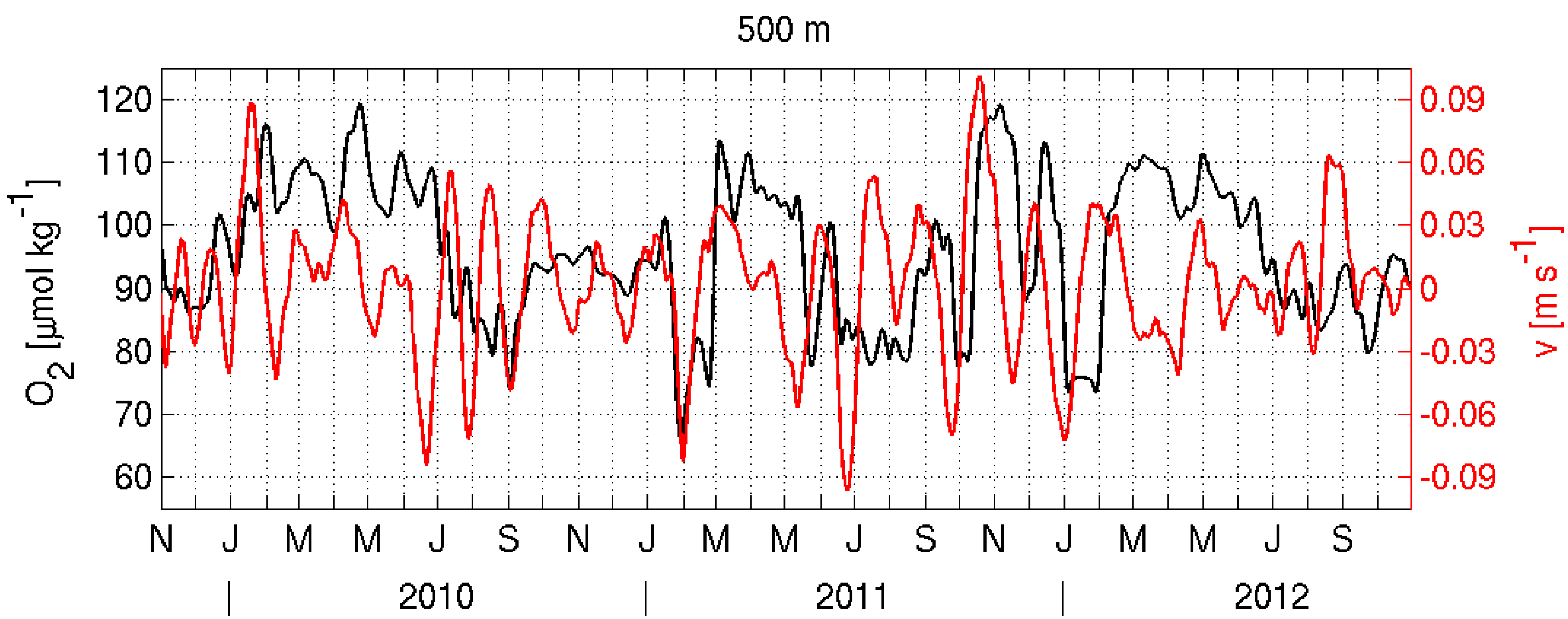
Oxygen time series along 23°W



Oxygen and velocity time series at 5°N, 23°W



<u>time series correlation:</u>

$$F = \langle v' O_2' \rangle$$

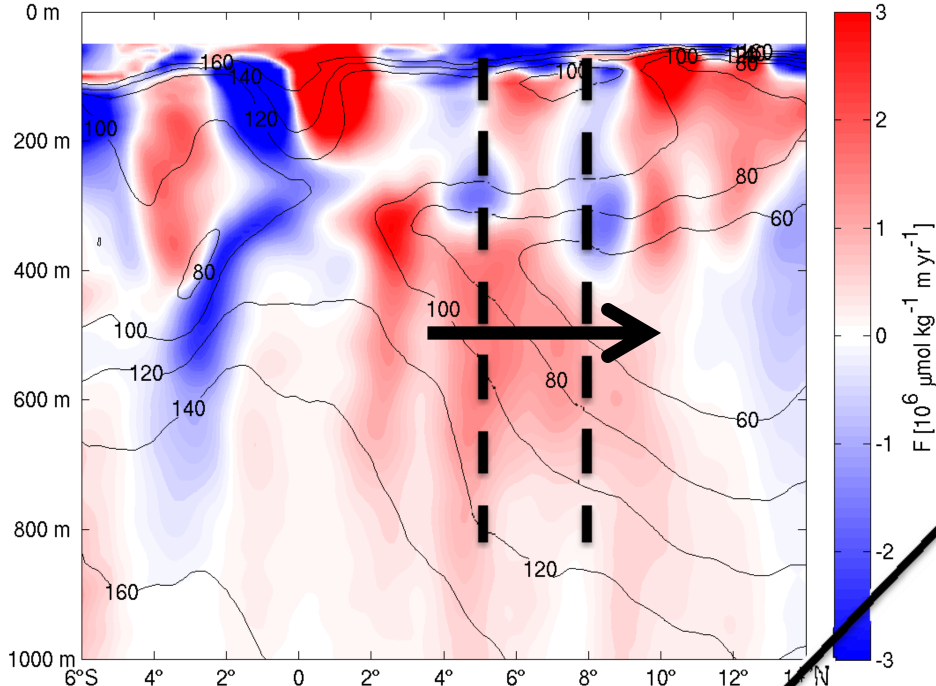
where

$$v = \langle v \rangle + v' \qquad O_2 = \langle O_2 \rangle + O_2'$$

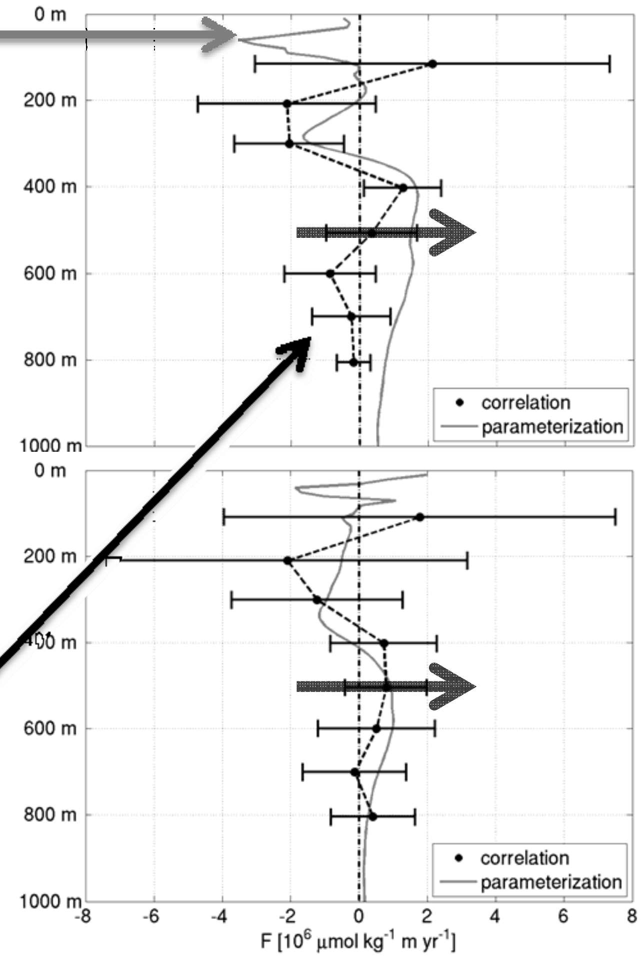
(Reynolds decomposition)

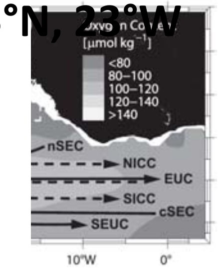
Eddy-Driven Meridional O_2 flux along 23°W

(I) $F = -K_e \dfrac{dO_2}{dy}$



mooring data, 5°N and 8°N





t et al. (2010)

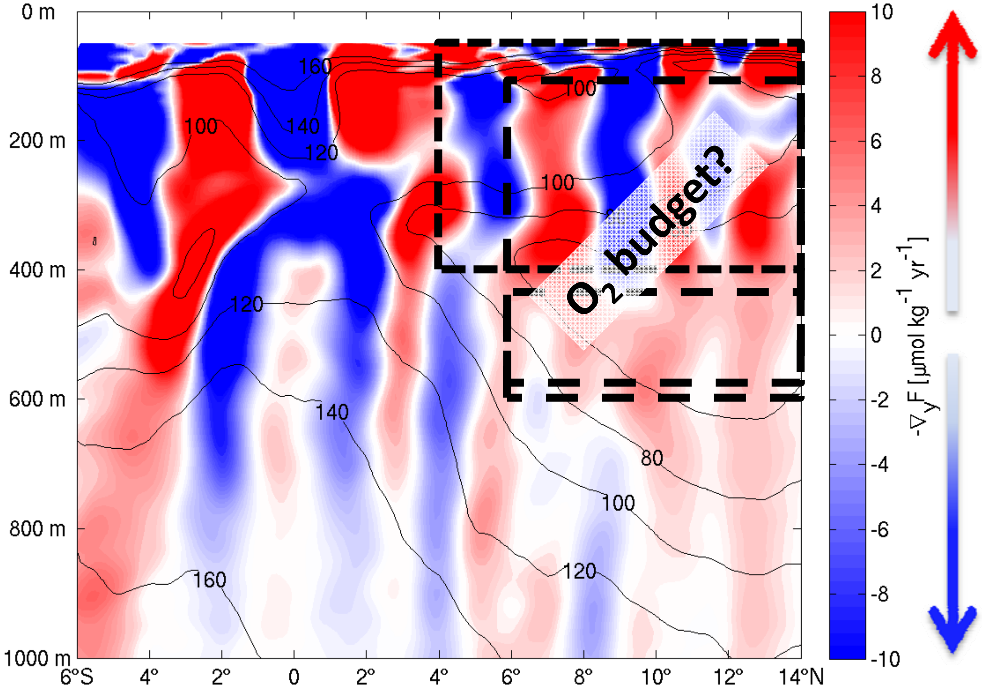
(II) $F = \langle v' O_2' \rangle$

northward O_2 flux at 400m-600m

Eddy-driven meridional O_2 supply along 23°W

$$-\frac{dF}{dy} = \frac{d}{dy}\left(K_e \frac{dO_2}{dy}\right)$$

Meridional O_2 flux divergence



convergence of O_2 flux

divergence of O_2 flux

450m-600m: O_2 supply due to mesoscale (2.1 µmol kg^{-1} yr^{-1})

above 400m: bands with strong O_2 flux divergence/convergence
→ associated with mean zonal currents

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O_2 budget

$$aOUR + O_{2,dia} + R^{(1)} = 0$$

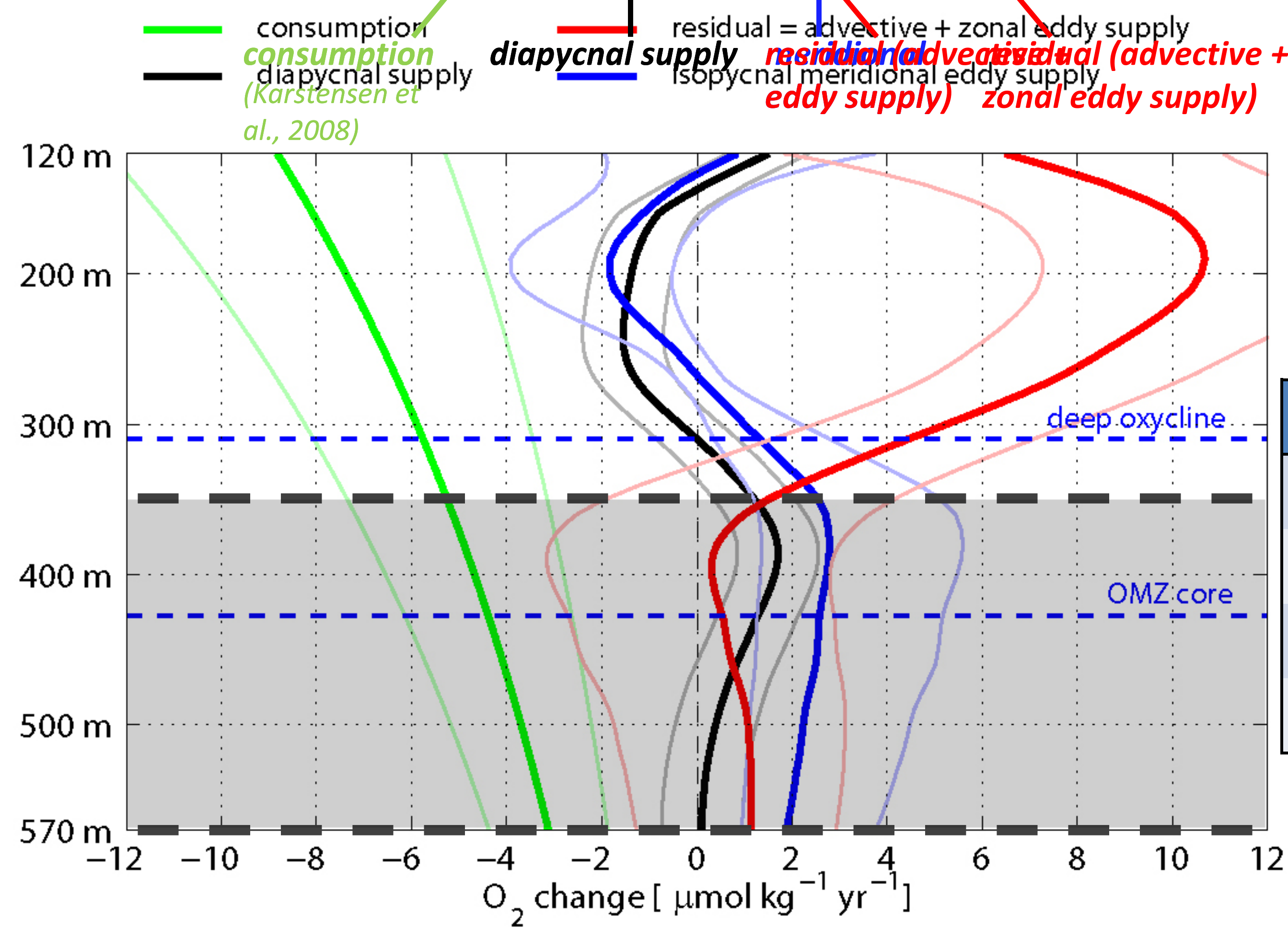
$$aOUR + O_{2,dia} + O_{2,y,eddy} + R^{(2)} = 0$$

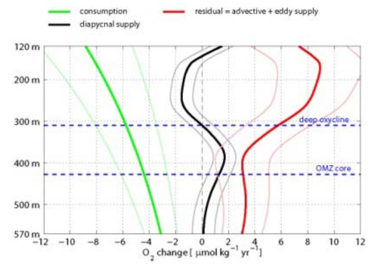
consumption (Karstensen et al., 2008)

diapycnal supply

residual (advective + eddy supply)

residual (advective + zonal eddy supply)





Fischer et al. (2013)

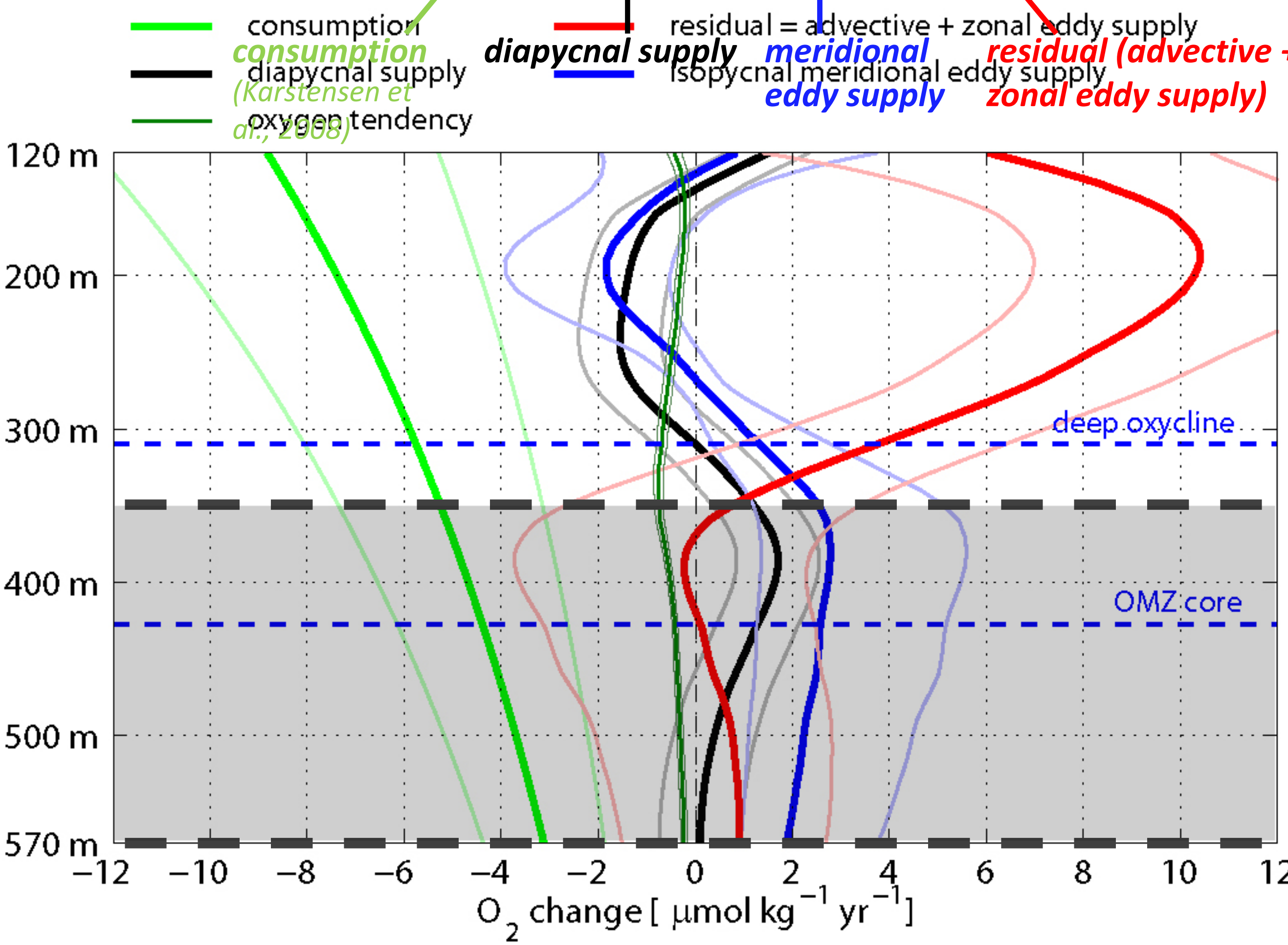
average between 350m - 570m

Term	µmol kg^{-1} yr^{-1}	% *aOUR*
aOUR	-4.1	---
$O_{2,dia}$	0.9	~20 %
$O_{2,y,eddy}$	2.4	~60 %
$R^{(2)}$	0.8	~20 %

O_2 budget

$$aOUR + O_{2,dia} + O_{2,y,eddy} + R^{(3)} = \partial_t O_2$$

consumption (Karstensen et al., 2008) | ***diapycnal supply*** | ***meridional eddy supply*** | ***residual (advective + zonal eddy supply)*** | ***O_2 tendency** (Brandt et al., 2010)*



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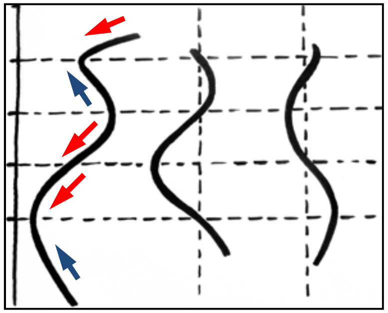
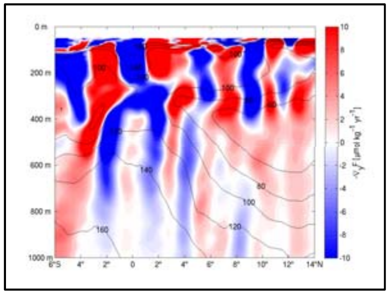
Summary



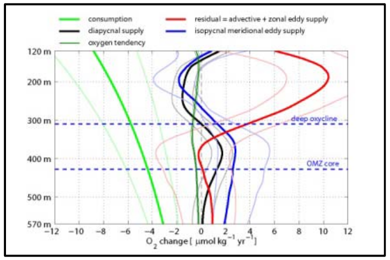
Diapycnal diffusivity K larger than expected, constant in 150 – 500m depth

Maximum diapycnal supply near OMZ core



Above 400m: bands with O_2 flux divergence/convergence associated with mean zonal currents

450m – 600m: homogeneous eddy-driven meridional O_2 supply

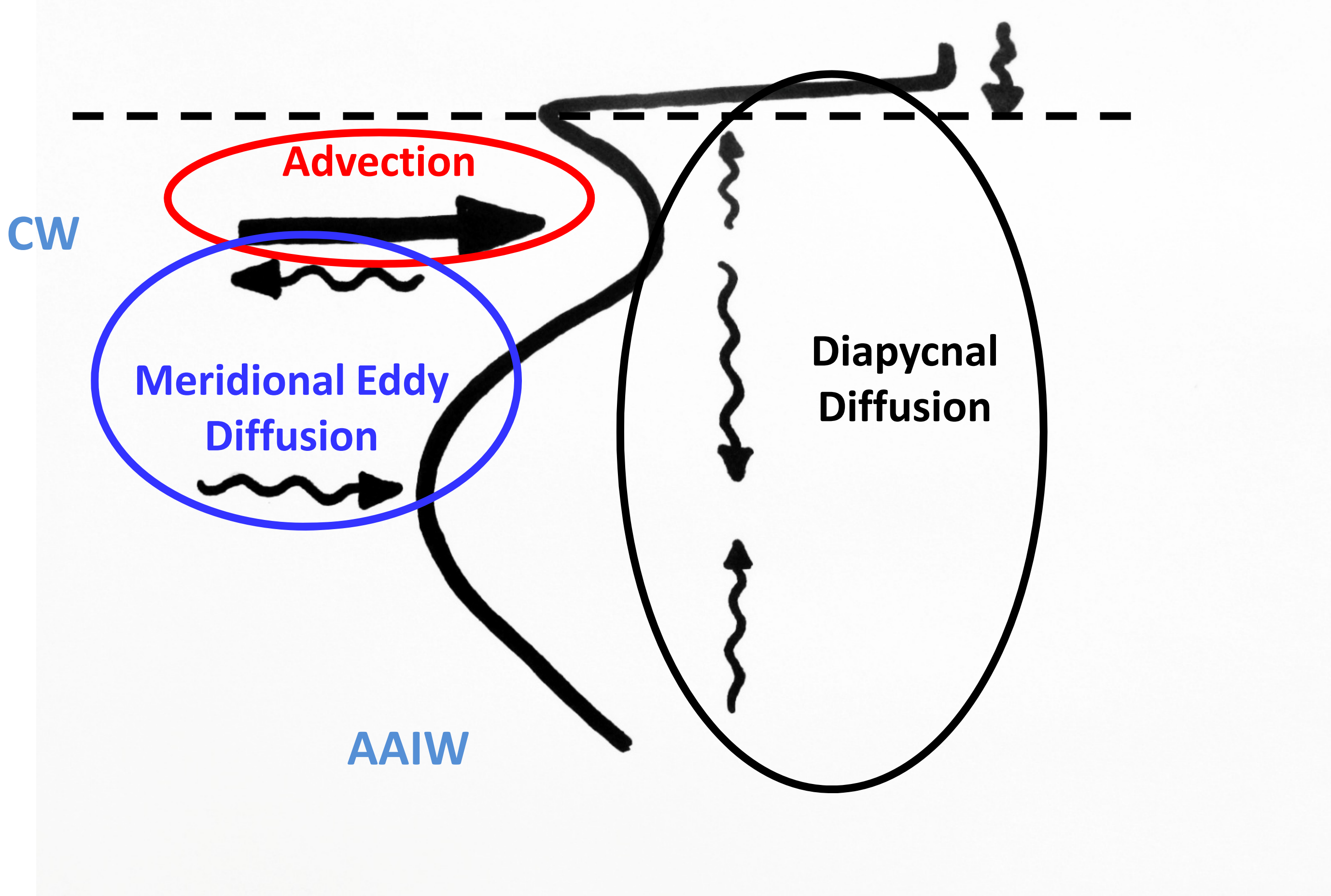


OMZ core depth: mainly diapycnal (up to 30%) and meridional eddy supply (>50%)

Above OMZ core depth: strong residual supply (associated with mean zonal currents)

Summary

Main oxygen supply processes in the TNEA OMZ (recent interpretation)

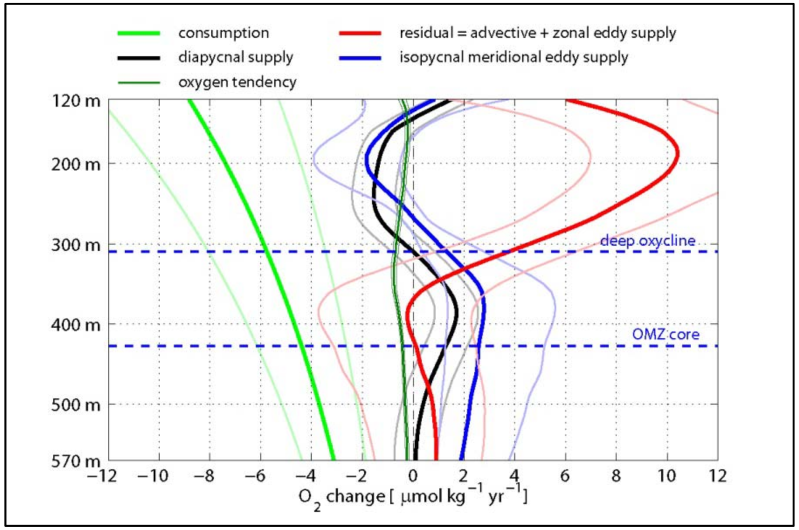


Outlook

Expand the analyses to 800m depth (AAIW)

Main missing term: mean zonal advection

Why is there that jump at 300m?



Tracer Release Experiment (OSTRE) in SFB phase II (2012 – 2015):
Measure integrative lateral diffusivity K_e in OMZ core

Thank you for your attention

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BMBF NORDATLANTIK